NASA TN D-263

NASA TN D-263

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198527
P-46

TECHNICAL NOTE

D-263

EFFECTS OF MELTING PRACTICE AND ALUMINUM COATING ON THE LIFE OF GMR 235 BUCKETS OPERATED AT 1650° F IN A TURBOJET ENGINE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON March 1960

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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EFFECTS OF MELTING PRACTICE AND ALUMINUM COATING ON THE LIFE OF GMR 235 BUCKETS OPERATED AT 1650° F IN A TURBOJET ENGINE

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SUMMARY

An investigation was conducted to determine the effects of melting practice and aluminum coating on the life of GMR 235 buckets operated at 1650° F in a turbojet engine. The buckets were obtained from a commercial source. The melting practice consisted of vacuum melting or air melting of master heats. The master heats of each melting practice were remelted as subheats under a cover of argon atmosphere and were poured to bucket configuration in investment molds purged with argon. Aluminum coating of buckets was accomplished by dipping and diffusion heat treating.

The evaluation of the GMR 235 buckets was made in a J33-9 engine operating under cyclic conditions. A single cycle consisted of a 15-minute rated-speed (11,500 rpm) interval followed by an approximate 5-minute idle-speed (4000 rpm) interval. The investigation indicated that vacuum-melted buckets had better than twice the life of air-melted buckets when life was based on time to fracture. However, there did not appear to be an appreciable difference between vacuum-melted or air-melted buckets when performance was based on time to cracking of the buckets by thermal fatigue. Aluminum coating appeared to improve the resistance to thermal fatigue and the time to fracture of the air-melted buckets; however, other factors present in the fabrication and testing of these buckets may have contributed to their apparent better performance. The improvements thus could not be attributed to aluminizing alone. Aging of air-melted buckets did not significantly affect performance with respect to crack formation or time to fracture. Diffusion heat treatment alone slightly decreased the thermal-fatigue resistance of vacuum-melted and air-melted buckets but increased slightly the time to fracture of air-melted buckets.

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INTRODUCTION

For some time the operating temperatures of turbojet bucket alloys were limited to the relatively low use temperature of approximately 1500° F. However, during the past several years significant increases in the high-temperature strength of nickel-base alloys have been obtained through alloy development and the utilization of vacuum-melting practices. This increase in strength naturally suggested that an increase in operating temperature was feasible.

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For the past several years, Lewis Research Center has tested some of the newer alloys at increasing operating temperatures. Increases in operating temperatures were coincidental with the relative increase in strength obtained in the alloys. Studies of the performance of Inconel 700 at 1625° F (ref. 1), alloy S-816 plus boron, modified S-816 plus boron, and Guy alloy at 1650° F (refs. 2 and 3) in J33 engines, and Udimet 500, B and B, SEL-1, and Inconel 713 alloys at 1700° F (ref. 4) in a J47 engine have shown that high-strength alloys can be operated at temperatures above 1500° F and yield acceptable performance.

GMR 235, a nickel-base alloy developed to operate at a temperature of 1500° F for 100 hours at a stress as high as 34,000 psi (ref. 5), also appeared to have potential for operation at 1650° F. Tests (ref. 5) indicated that cast GMR 235 possessed good thermal-shock and mechanical-fatigue properties and that the stress-rupture strength of the alloy could be improved by aging for 5 hours at 1800° F. These data were obtained from material air-melted in master heats that were remelted and cast under an argon cover in subheats. Later investigations (ref. 6) indicated that vacuum melting of master heats improved the properties of GMR 235 over those obtained with the air-melting practice. Private communications with the Allison Division of General Motors indicated that the thermal-fatigue resistance of GMR 235 could be improved further by applying an aluminum-dip coating.

Since GMR 235 appeared to have potential as a 1650° F bucket material and since variations in melting practice and heat treatment appeared to further improve alloy properties, an engine investigation at this temperature was initiated. The specific objectives of this investigation were to determine:

(1) The degree of improvement in engine life of GMR 235 vacuum-melted buckets over air-melted buckets

(2) The effect of aluminum coating on the life and thermal-fatigue properties of both the vacuum-melted and air-melted buckets

(3) The effect of an aging treatment on the life of air-melted buckets

Eight groups of GMR 235 buckets were evaluated in this investigation. Of the eight groups, four were produced from vacuum-melted master heats and the other four groups from air-melted master heats. All of the subheats, cast from these two types of master heats, were cast under a cover of argon into preheated investment molds purged with argon. Some buckets from both the vacuum-melted and the air-melted master heats were coated by an aluminum-dipping process. The buckets were evaluated in a J33-9 engine. The engine was operated under cyclic conditions in which each cycle was of 20-minute duration and consisted of a 15-minute rated-speed (11,500 rpm) interval followed by approximately a 5-minute interval at idle speed (4000 rpm). During the rated-speed interval, the centrifugal stress at the bucket midspan was approximately 20,000 psi and the midchord, midspan temperature was maintained at 1650° F. The engine test was terminated after 269 hours of accumulated rated-speed operating time. Buckets from each group were subjected to macrographic inspection, metallographic studies, and hardness determinations before and after the engine test.

APPARATUS, MATERIALS, AND PROCEDURE

Test Engine

A conventional J33-9 engine was modified to permit operation of buckets considerably above the design temperature of 1500° F. The major modification consisted of introducing compressor-air bleedoff ports in the spacers located between the diffuser and air adapters. By bleeding 3 percent of the compressor air, it was possible to operate the engine sufficiently below the compressor surge line to prevent vibrational problems while a bucket temperature of 1650° F was maintained. In addition, the standard turbine stator blade assembly was replaced by a later engine model (J33-33) stator assembly. This change was made because of availability considerations and required that the test buckets include features of both the J33-9 and the J33-33 buckets. Hence, the test buckets were cast with J33-33 airfoils and with the J33-9 base configuration. These buckets were inserted into a disk made from S-816 alloy.

Turbine Buckets

The GMR 235 buckets were obtained from a commercial source and were produced as follows: The buckets were precision cast by the lost-wax process from master heats of the alloy produced by either vacuum melting or air melting. The master heats were divided into subheats of such a size as to produce a single bucket. The subheats were remelted and cast under a cover of argon into preheated investment molds purged with argon. Buckets produced from two vacuum-melted master heats (hereinafter referred to simply as "vacuum-melted" buckets) and four air-melted master heats (hereinafter referred to as "air-melted" buckets) were evaluated. The certified chemical analyses of these six heats are given in table I.

The melting practice and heat treatments pertaining to each group of buckets studied in this investigation are shown in table II. In addition, the groups that were aluminum-dipped (hereinafter referred to as "aluminized" buckets) are identified. Table II also shows that one of the groups of air-melted buckets was aged prior to testing. Although the exact coating procedure was not made available to the Lewis Research Center, in general it included these major steps: (1) cleaning in a salt bath, (2) immersion in a molten aluminum bath (thickness of coating is proportional to time that buckets are kept in aluminum bath), (3) immersion in a salt bath to remove excess aluminum (normal sag and runoff of aluminum), and (4) a 3-hour diffusion heat treatment at $2040^{\circ}\pm10^{\circ}$ F. In order to determine whether the aluminizing or the diffusion heat treatment were the controlling factor should improvements over as-cast bucket life result, it was also necessary to engine-test groups of uncoated air-melted and vacuum-melted buckets subjected to the same diffusion heat treatment. An aging treatment of 5 hours at 1800° F (to improve stress-rupture strength) was applied to some of the as-cast air-melted buckets. No aging treatment was given vacuum-melted buckets because of an insufficient supply.

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Buckets free of defects detectable by radiographic inspection, and containing only a limited number of surface defects indicated by fluorescent oil penetrant (PE zyglo) examinations, were used. The buckets used in the performance test were examined with PE zyglo periodically during the evaluation program for surface defects and cracks.

Engine Operation

The J33-9 test engine was operated under cyclic conditions in which a single cycle was of 20-minute duration: 15 minutes at rated speed (11,500 rpm) and approximately 5 minutes at idle speed (4000 rpm). Acceleration from idle speed to rated speed and deceleration from rated speed to idle speed were accomplished in similar periods of time, approximately 15 seconds. During the rated-speed operation the midspan, midchord bucket temperature was measured with thermocouples mounted in two S-816 buckets (shortened to reduce centrifugal stress). The temperature measurements, taken through a system of slip rings, were recorded on an electronic potentiometer. Rated-speed bucket stress (20,000 psi at midspan) and temperature (1650° F at the midchord, midspan position) were controlled by engine speed and exhaust-nozzle opening, respectively. Engine operation was interrupted to replace failed buckets, to replace other failed engine components, for major overhauls, and at the end of each work day. The test was terminated after 269 hours of rated-speed operation. The times of failure reported herein refer to the cumulative time at rated speed only.

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Stress and Temperature Distributions in Turbine Buckets

The centrifugal stress and average spanwise temperature distributions encountered during rated-speed operation are shown in figure 1. The centrifugal stress distribution along the span of the GMR 235 buckets was determined by a graphical method that takes into account the bucket geometry, density, radius of rotation, and rotational speed (ref. 7).

The spanwise bucket temperature distribution at the midchord position was determined during the initial stage of operation and was checked after each major overhaul. Four S-816 thermocoupled buckets were used to obtain the temperature distribution initially and after each major overhaul (ref. 8). The temperature distribution plotted in figure 1 represents an average of the temperature distributions. For test operation, only two thermocoupled buckets were used.

Bucket Elongation Measurements

Elongation measurements were taken on 1/2-inch gage lengths scribed on the convex side near the trailing edge of the buckets, as shown in figure 2. Elongation measurements were taken on two buckets of each of the seven groups that were inserted in the engine at the beginning of the test. Measurements were taken at convenient intervals during the test. The elongation of each scribed segment was measured with an optical micrometer having a sensitivity of 0.0001 inch. Accuracy of the elongation measurement was influenced by the degree of bucket oxidation, distortion, and warpage. Because of these factors, the actual reproducibility of an elongation reading was of the order of ± 0.2 percent in the 1/2-inch gage length considered.

Macroexamination of Buckets

Three as-cast vacuum-melted buckets and three as-cast air-melted buckets were macroetched in an 80 percent hydrochloric acid, 20 percent hydrogen peroxide solution to give an indication of grain size and casting flaws. All operated buckets were examined visually at low magnifications (up to X20) and with zyglo techniques to determine, as nearly as possible, the mechanism of failure or the condition if unfailed.

Failure Mechanisms

Many small cracks along the bucket leading edges were observed at the periodic inspections during the engine test. This type of cracking has been observed previously in J47 engine tests (refs. 4, 9, and 10) and has been shown to be caused by thermal-stress fatigue (ref. 10). Although it has not been shown that the cracks observed in J33 buckets were thermal-fatigue-induced, it is very likely that the failure mechanism was the same as in the J47 buckets. Thus, buckets containing leading-edge cracks were termed thermal-fatigue failures; however, buckets were not removed from the engine because of these thermal-fatigue cracks. Only buckets that fractured or were in imminent danger of fracture were removed. The fracture mechanisms were classified as follows:

(1) Stress-rupture: Bucket failure occurred by cracking within the airfoil or by fracturing in an irregular, jagged, intercrystalline path.

(2) Mechanical fatigue: Cracks progressed from nucleation sites - usually at or near the leading or trailing edges - in straight paths, which frequently were smooth; they often showed progression lines or concentric rings and appeared to be transcrystalline.

(3) Stress-rupture and mechanical fatigue: Bucket failures appeared to be caused by a combination of two mechanisms, stress-rupture and fatigue. The fracture surface consisted of a small area having characteristics of stress-rupture and a larger area with fatigue characteristics (a relatively smooth failure area showing concentric rings). A further criterion can be the appearance of secondary stress-rupture cracks near the nucleation site of the main crack.

(4) Damage: Buckets showing nicks or dents so extensive that fracture would probably occur in a short time were removed from the engine and were considered to be damage failures. Also, buckets in which fracture was seen to have propagated from a nick or dent were considered damage failures. Damage failures were not considered in the analysis of the data.

Metallographic Studies of Buckets

Metallographic specimens of airfoil sections were taken from new buckets, as shown in figure 3. One bucket of each group tested, except the diffusion-heat-treated groups, was examined. The diffusion-heat-treated buckets were not examined because the structure was believed to be similar to that of the aluminized buckets of the respective melting practice (vacuum or air). Metallographic studies also were made on specimens taken near the origin of failure of the first and last bucket failures of each group tested. In addition, extensive studies were made on buckets that showed excessive stress-rupture cracking or thermal-fatigue cracking on the leading edges. Specimens were examined in both the unetched and etched condition. The specimens were electrolytically etched in a solution containing 40 percent c.p. hydrochloric acid, 10 percent c.p. nitric acid, and 50 percent distilled water.

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Hardness Measurements

Rockwell C hardness determinations were made on specimens taken from the central section of buckets, as shown in figure 3. Hardness specimens were taken from as-received, first-fractured, and last-fractured buckets of each group. The hardness was measured at several spanwise locations beginning 1/2 inch above the base.

PREDICTED BUCKET LIFE BASED ON STRESS-RUPTURE CONSIDERATIONS

By use of the stress and temperature distributions determined for the buckets (fig. 1) in conjunction with stress-rupture data for GMR 235 alloy, it is possible to approximate the life expectancy of these buckets if the sole cause of failure is assumed to be stress-rupture. Predicted life for the as-cast air-melted buckets is shown in figure 4. This prediction was based on the manufacturer's stress-rupture data for air-melted GMR 235 material (not the same heats of material used in this investigation).

Predicted lives of GMR 235 vacuum-melted and aluminized buckets were not determined because it was felt that the buckets needed for the engine test could not be sacrificed for stress-rupture data.

The life values shown in figure 4 were determined by interpolating between isothermals of the manufacturer's stress-rupture data for the stress and temperature conditions prevailing at incremental distances along the span of the buckets. The minimum expected life was determined to be 68 hours. This minimum life was coincident with a distance 2.25 inches above the base, and stress-rupture failures would be expected to occur in a region near this point. If stress-rupture is assumed to be the sole failure mechamism, this region may be considered the critical zone of the buckets. Experience has shown, however, that factors other than stress-rupture, such as vibrational stresses, thermal cycling, and corrosion, influence the life of the buckets and may cause failure to occur outside of the critical zone and at times other than those predicted on the basis of centrifugal stress and temperature (ref. 11).

RESULTS

Engine Operating Results

Fracture mechanism. - Figures 5 to 8 show typical failures of GMR 235 buckets encountered during testing. Figure 5 shows typical stress-rupture cracking that ultimately would lead to fracture. The cracks occurred in various locations along the span from 1.5 to 3.2 inches above the base platform. These cracks were intergranular in nature, and the majority of them occurred in the critical zone (fig. 4), where stress-rupture would be expected. Figure 6 shows a failure that was initiated by stress-rupture and was fractured by a combination of stress-rupture and mechanical fatigue. Figure 7 shows the progression of a typical mechanical-fatigue failure until the cross-sectional area was too small to support the imposed load and the final separation occurred as a tensile failure. Figure 8 shows a slightly damaged bucket, which indicates that GMR 235 can react in either a brittle or a ductile manner when impacted by flying fragments of fractured buckets. The majority of the damage-failed buckets showed a brittle type of fracture, however. All of the vacuum-melted buckets failed as a result of damage or fatigue, whereas the majority of the air-melted buckets failed by stress-rupture cracking.

Bucket life. - The operating life and types of fractures encountered with each of the eight groups of GMR 235 buckets evaluated in this investigation are presented graphically in figure 9 and are tabulated in table III. A comparison of the average life of the vacuum-melted buckets and that of the air-melted buckets (i.e., time to fracture or crack by stress-rupture) shows that the vacuum-melted buckets had better than twice the life of the air-melted buckets. The arithmetic average life of the vacuum-melted buckets was greater than 250 hours (13 buckets had not failed at the termination of engine testing), while the average life of the air-melted buckets was 102 hours.

Damage-induced fractures precluded valid comparisons of life of the different vacuum-melted buckets between individual groups or with their corresponding groups of air-melted buckets.

Group-to-group comparison of air-melted buckets was possible and shows that the aluminized buckets, group 8, had the longest average life: 122 hours. The diffusion-heat-treated buckets, group 6, had an average life of 100 hours; as-cast buckets, group 5, and aged buckets, group 7, had average lives of 94 hours and 89 hours, respectively.

Thermal-stress-fatigue cracking. - Both vacuum- and air-melted GMR 235 buckets appeared to be susceptible to leading-edge cracking when operating at 1650° F. Thermal-stress-fatigue cracking was detected by zyglo inspection techniques after only 24 hours of rated-speed operation. When first detected by PE zyglo, the cracks were so fine that they could not be successfully photographed. With continued operation, the cracks increased slightly in size. Figure 10 shows the nature of these cracks after prolonged operation (269 hr of rated-speed time); this picture was taken after the oxide scale had been removed. Table IV summarizes the data obtained on crack formation and growth with accumulated rated-speed operation time. The number of cracked buckets plotted as a function of rated-speed operating time is shown in figure 11. The figure indicates that over 50 percent of the buckets cracked in 38 hours and that 100 percent cracked in 120 hours. Aluminizing of the vacuum-melted buckets (group 2) caused a slight increase in the average time to crack formation relative to the vacuum-melted as-cast condition (group 1) (56 hr against 44 hr, respectively). The data indicate that the diffusion heat treatment was detrimental, since group 3 had the poorest resistance to cracking.

Figure 11 further indicates that the aluminized air-melted buckets had a better crack resistance than did the as-cast air-melted buckets. The aluminized buckets (group 8) had an average time to crack formation of 86 hours as compared with 41 hours for the as-cast material (group 5). It should be recalled that the aluminized buckets were from two heats which differed from the as-cast heat used for a basis of comparison. The diffusion-heat-treated air-melted buckets had a lesser crack resistance than did the as-cast buckets.

<u>Bucket elongation during engine operation</u>. - The percent elongations occurring in positions 2 ($1\frac{1}{2}$ to 2 in. above the base) and 3 (2 to $2\frac{1}{2}$ in. above the base) (see fig. 2 for positions) during rated-speed operation are plotted in figure 12 for buckets of groups 1 to 7. Positions 2 and 3 were selected because they are located near the critical zone of the buckets, where the combination of stress and temperature would be expected to cause plastic deformation to be most pronounced. The data show that the buckets generally exhibited rather low elongation. The maximum elongation was of the order of 1.2 percent and occurred in an air-melted bucket from group 7.

Based on bucket elongations, the vacuum-melted material had a much greater resistance to creep than the air-melted material. For example, at 50 hours of rated-speed operation, the maximum elongation in the vacuum-melted material (group 4, position 3) was 0.14 percent as compared with the maximum elongation of 1.17 percent in the air-melted material (group 7). The steep slope of the elongation curve for the group-7 buckets indicates that third-stage creep may have been encountered prior to 50 hours of rated-speed operation. Among the different groups of vacuum-melted material after 150 hours of rated-speed operation, the buckets given the diffusion heat treatment (groups 2 and 3) had a lower elongation than the as-cast groups (groups 1 and 4). The percentage elongations were approximately 0.15 percent for groups 2 and 3 and 0.35 percent for groups 1 and 4. In these comparisons it should be recognized that the degree of reading reproducibility was ±0.2 percent; consequently, the comparisons made are more qualitative than quantitative.

Macro- and Micro-Examination of Buckets

As-received buckets. - Examples of macrograins present in vacuum-melted and air-melted as-cast buckets (groups 1 and 5) are shown in figure 13. The grains of the vacuum-melted buckets were equiaxed and were uniformly fine throughout the airfoil. The grains of the air-melted buckets varied from equiaxed, uniformly fine grains in the upper two-thirds of the airfoil to columnar, medium-sized grains in the lower third of the bucket airfoil.

Typical microstructures of as-received GMR 235 buckets (groups 1, 3, 5, 7, and 8) are shown in figure 14. As stated previously, metallographic studies were not made on as-received diffusion-heat-treated buckets of either vacuum- (group 3) or air-melted material (group 6). Only a limited supply of buckets was available for study, and it was believed that these buckets would have the same structures as the aluminized buckets of each melting practice.

All buckets examined contained a "Chinese script" type of microconstituent that has been determined to be a complex boride (ref. 5). The as-cast buckets, figures 14(a) and (c), contained some finely dispersed precipitates that may be Ni_3Al type intermetallic compounds, which are commonly present in high-nickel alloys containing aluminum (ref. 12). However, the aluminized GMR 235 buckets, figures 14(b) and (d), lacked the fine precipitate. The absence of fine precipitates in the photomicrographs of the aluminized buckets was attributed to solutioning by the diffusion heat treatment (2040° F for 3 hr). The heat treatment did not appear to alter appreciably the "Chinese script" type of precipitates. Figure 14(e) shows a representative microstructure of the aged (5 hr at 1800° F), air-melted buckets (group 7). The aging treatment also appears to have caused a slight amount of solutioning.

The microstructure of the "aluminum coating" consists of an outside envelope and a thin two-phase region at the GMR 235 matrix - aluminum-coating interface (fig. 15). A microhardness check of the coating showed the outside envelope to be equal in hardness to the matrix and the two-phase region to be appreciably harder. From these observations, it was concluded that the outside envelope was an aluminum-rich nickel alloy with fine precipitates and that the two-phase region probably consisted of the aluminum-rich matrix and massive agglomerations of Ni_3Al.

The thickness of the coating varied slightly and ranged from approximately 0.6 mil on the edges to approximately 0.4 mil on the body of the airfoil. Cracks were noted along the coating - base-metal interface, as shown in figure 16. The cracks were small and occurred at random locations in the buckets and, in some instances, extended from the interface to the outside of the coating (not shown in fig.). Their presence could not be detected by PE zyglo inspection, so it is possible that they occurred during specimen preparation.

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Operated buckets. - Metallographic study of the operated buckets showed that aging of the alloy occurred during engine operation. Figure 17 shows typical microstructures of operated buckets. A comparison of photomicrographs of aluminized, diffusion-heat-treated as-received and operated buckets (figs. 14(b) and (d) with 17(b) and (d)) shows that appreciable aging occurred during engine operation. The greatest amount of precipitation during engine operation occurred in the aluminized air-melted buckets, group 8. Another point that may be noted from figures 14 and 17 is that the precipitates in the as-cast air-melted and vacuum-melted material behave differently during engine operation. The precipitates in the as-cast air-melted buckets, group 5, appear to have agglomerated in localized areas (fig. 17(c)). The vacuum-melted as-cast buckets, after a much greater period of engine operation, show considerably less tendency toward precipitate agglomeration.

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Figure 18 shows photomicrographs of typical leading-edge cracks observed in the GMR 235 buckets. The cracks followed either a transgranular path (fig. 18(a)) or an intergranular path (fig. 18(b)). In some instances, the cracking appeared to originate in the scale that formed on the buckets during operation (fig. 18(c)). Generally, the cracks propagated at a very slow rate; the longest crack detected was of the order of 0.15 inch.

Hardness Data

The results of the Rockwell C hardness determinations made on as-received, first-fractured, and last-fractured buckets of each group are given in table V. (Hardness determinations were not made on as-received diffusion-heat-treated buckets, groups 3 and 6, because of a limited supply of material and because it was felt that these buckets would have the same hardness as the aluminized buckets, groups 2 and 8.) The hardness readings along the span of the as-received buckets were essentially uniform. The average hardness of the groups of vacuum-melted buckets ranged from Rockwell C-29.4 to C-31.3, and that of the air-melted groups ranged from C-28.0 to C-29.4.

The GMR 235 buckets hardened during operation; however, the increase in hardness was not uniform along the span, as can be noted in table V. Greatest hardening generally occurred in the lower part of the airfoil, and a maximum increase of nine Rockwell C points was observed. The hardness at the midspan of the operated buckets was generally equivalent to that of the as-received buckets.

DISCUSSION OF RESULTS

The results of this investigation may be analyzed from two standpoints: first, the time necessary to cause complete fracture of the buckets; and second, the time necessary to produce thermal-fatigue cracks on the leading edges.

Bucket Performance Based on Time to Fracture

With regard to the fracture aspect, it was shown that the vacuum-melted groups of buckets had significantly greater life in the engine than did the air-melted buckets. In fact, the average lives of the vacuum-melted buckets were greater than 250 hours as compared with 102 hours for the air-melted buckets.

Reasons for the superiority (on the basis of time to fracture) of the vacuum-melted buckets were sought. A comparison of the chemical analyses of the various groups of buckets showed that the compositions were essentially the same; at least, the differences that did occur could be expected to result from the differences in melting practice. There was a difference in the silicon content in that the vacuum-melted material had only 0.05 percent as opposed to 0.38 percent for the air-melted material. In addition, there was a slight difference in the average titanium-aluminum ratios between the two major groups of buckets: The ratios of the vacuum-melted master heats and the air-melted master heats were 0.661 and 0.650, respectively.

An indication that the microstructure of the vacuum-cast materials was more stable than the structure of the air-melted buckets was revealed in two ways: First, the as-cast air-melted operated buckets seemed to show an agglomeration of precipitates (fig. 17(c)); this agglomeration occurred after 121 hours of operation. On the other hand, the as-cast vacuum-melted operated buckets showed no appreciable agglomeration of precipitate after 213 hours (fig. 17(a)). An additional point that might be made is that the aluminized vacuum-melted buckets (fig. 17(b)) did not age to as great a degree (microstructurally) as did the aluminized air-melted buckets (fig. 17(d)); the structure of both of these groups of buckets appeared to be solution-treated in the as-aluminized (untested) conditions (figs. 14(b) and (d)). A further indication of the instability of the structure of the air-melted material relative to the vacuum-melted material may be had by comparing the elongation curves in figure 12. The vacuum-melted groups (groups 1 to 4) did not elongate as much as the air-melted groups (groups 5 to 7).

In order to determine the effect of the aluminizing on the performance of the buckets, the vacuum-melted and the air-melted bucket groups must be considered separately. In the case of the vacuum-melted buckets, many damage fractures occurred, and a conclusion that one group of buckets was superior to another in performance (based on time to fracture) could not be made. Even though a number of buckets remained intact at the end of the test, it was not deemed feasible to statistically compare the performance of the different groups.

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In the case of the air-melted groups, only the aluminized group had an average operating life somewhat greater (28 hr) than that of the as-cast buckets. This greater bucket life, which is statistically significant, may have resulted from the aluminizing process; but it must be considered in the light of two additional factors. First, the aluminized bucket group came from different master heats than those of the control as-cast group. Second, the aluminized buckets were installed in the engine as replacements when other buckets fractured and hence did not run exactly concurrently with the control group. Therefore, although the performance of the aluminized air-melted buckets appeared somewhat better than that of the as-cast air-melted buckets, it should not be concluded that aluminizing alone improved the life of the buckets.

Bucket Performance Based on Thermal-Fatigue Cracking

Thermal-stress-fatigue cracking of J33 buckets during engine operation was encountered for the first time in this investigation; however, this mode of failure was previously evidenced in tests in J47 engines (refs. 4 and 9). An investigation of the causes of thermal-fatigue cracking (ref. 10) indicated that the cracking in J47 engines resulted from thermal gradients produced in buckets during engine starts.

Thermal-fatigue cracks were observed in some buckets of all groups in 50 hours or less and in all buckets in 120 hours. In the case of the vacuum-melted groups of buckets that came from a single master heat, aluminizing did not significantly improve thermal-fatigue crack resistance. Aluminized air-melted buckets exhibited a somewhat better crack resistance than any other group of GMR 235 buckets tested. This superior crack resistance, though statistically significant, should be considered in the light of other factors that may have influenced the results. As stated earlier, the aluminized air-melted buckets were produced from master heats different from those of the control buckets and were inserted into the test engine as replacement buckets.

The aged group of air-melted buckets (group 7) did not exhibit a different thermal-fatigue crack resistance than that of the as-cast group (group 5).

Cracks in the leading edges can make the buckets susceptible to fracture by other failure mechanisms, such as mechanical fatigue or stress-rupture. Table III indicates that all of the fractures of the vacuum-melted buckets, except damage fractures, occurred by mechanical fatigue and originated at the leading edge. This suggests that the thermal-fatigue cracks were the sources for the mechanical-fatigue failures. This assumption appears valid in light of other engine tests in which it was shown that mechanical fatigue progressed from thermal-fatigue cracks and thereby caused fracture to occur in times less than the expected life (ref. 9).

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SUMMARY OF RESULTS

The investigation of GMR 235 buckets of various melting practices and heat treatments in a turbojet engine at 1650° F disclosed the following results:

1. Based on the time to fracture, the vacuum-melted buckets had better than twice the life of the air-melted buckets. The arithmetic average life of the vacuum-melted buckets was greater than 250 hours, while that of the air-melted buckets was 102 hours.

2. From a practical standpoint, there did not appear to be an appreciable difference between the vacuum-melted and air-melted groups of buckets because leading-edge cracks had formed by thermal fatigue in all groups after the relatively short operating time of 50 hours.

3. In the case of the vacuum-melted groups of buckets (that came from a single master heat), aluminizing did not significantly improve thermal-fatigue crack resistance. The aluminized air-melted groups of buckets exhibited the best resistance to thermal-fatigue cracking. However, since these latter buckets were from a different heat than that of the as-cast buckets, and were inserted in the engine as replacement buckets and thus did not operate concurrently with the as-cast buckets, it should not be concluded that aluminizing alone could account for the somewhat superior performance.

4. The aged group of air-melted buckets did not exhibit a significantly different performance than that of the as-cast group with respect to thermal-fatigue crack formations or time to fracture.

5. Diffusion heat treatment alone appeared to decrease slightly the thermal-fatigue resistance of vacuum-melted and air-melted buckets but increased slightly the time to fracture of air-melted buckets relative to as-cast buckets.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, November 10, 1959

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TABLE I. - CHEMICAL COMPOSITIONS OF VARIOUS HEATS OF GMR 235 ALLOY BUCKETS

USED IN ENGINE EVALUATION AT 1650° F

Condition	Group	Heat number	Cr	Fe	C	Si	Ni	Mn	Ti	Al	Mo	B	Ti/Al ratio
Vacuum melted	1,2,3	88	16.20	10.75	0.14	0.05	Bal.	0.006	2.08	3.12	5.35	0.097	0.667
	4	33	15.85	10.25	.15	.05	Bal.	.005	2.20	3.36	4.95	.086	.655
Air melted	5,6	FB 985	14.98	9.43	0.18	0.37	Bal.	0.02	2.16	3.25	4.82	0.061	0.665
	7	FB 975	15.41	9.30	.17	.36			1.96	3.05	5.10	.057	.643
	8	FB 970	15.46	9.20	.15	.37			2.03	3.16	5.00	.067	.642
		FB 955	15.13	9.35	.17	.42			1.95	3.01	4.90	.062	.648

TABLE II. - PRETEST CONDITION OF GMR 235 ALLOY BUCKETS

Group	Master heat number	Melting practice	Condition of bucket (a)	Number of buckets evaluated	
				At start of test	Inserted as replacements
1	88	Vacuum-melted master heats; subheats melted and cast under argon	As cast	8	0
2	88	↓	Aluminum dipped and diffusion heat treated at 2040° F for 3 hr	↓	↓
3	88	↓	Diffusion heat treated at 2040° F for 3 hr	↓	↓
4	33	↓	As cast	↓	↓
5	FB 985	Air-melted master heats; subheats melted and cast under argon	As cast	8	0
6	FB 985	↓	Diffusion heat treated at 2050° F for 3 hr at NASA	8	0
7	FB 975	↓	Aged; that is, heat treated at 1800° F for 5 hr	4	4
8	[b]FB 970 FB 955	↓	Aluminum dipped and diffusion heat treated at 2050° F	0	8

[a]Aluminum-dip coating, diffusion heat treating, and aging done by General Motors Corp. except for group 6, which was diffusion heat treated at NASA.

[b]Heat numbers could not be separated because coating obliterated identification numbers.

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TABLE III. - ORDER OF FAILURE, ORIGIN OF FAILURE, AND TYPES OF FAILURES OBTAINED DURING EVALUATION OF GMR 235 BUCKETS IN A J33-9 ENGINE

(a) Vacuum-melted buckets

Group	Time to failure, hr	Type of failure	Location of failure		Remarks (a)
			Inches above base	Chordwise position	
1	160.2	Damage			
	160.2				
	200.2				
	213.0				
	213.5	Fatigue	2.2	Leading edge	
	224.2	Damage			
	268.2	Damage			
	268.6	Unfailed			
2	212.5	Fatigue	1.6	Leading edge	
	230.0	Damage			
	239.0	Fatigue	2.2	Leading edge	
	268.6	Fatigue	1.1	Leading edge	
	268.6	Unfailed			
	268.6				
	268.6				
	268.6				
3	189.0	Fatigue	2.2	Leading edge	
	200.2	Damage			
	204.8	Fatigue	2.6	Leading edge	
	230.2	Fatigue	2.4	Leading edge	
	268.6	Unfailed			
	268.6				
	268.6				
	268.6				
4	160.2	Damage			
	200.2				
	200.2				
	267.0				
	268.6	Unfailed			
	268.6				
	268.6				
	268.6				

TABLE III. - CONCLUDED. ORDER OF FAILURE, ORIGIN OF FAILURE, AND TYPES OF FAILURES OBTAINED DURING EVALUATIONS OF GMR 235 BUCKETS IN A J33-9 ENGINE

(b) Air-melted buckets

Group	Time to failure, hr	Type of failure (b)	Location of failure: Inches above base	Location of failure: Chordwise position	Remarks (a)
5	50.0				Removed for study of thermal-fatigue cracking
	64.7	S-R cracks	1.8	Midchord	
	74.5		2.1		
	99.0		2.2		
	99.0		1.8		
	99.0		2.2		
	99.0		2.0		
	120.8		2.2		
Av. life:	94				
6	74.5	S-R cracks	2.1	Midchord	
	74.5		2.0	Midchord	
	74.5		2.2	Trailing edge	
	84.3		1.4	Trailing edge	
	106.1		2.4	Midchord	
	125.8	S-R fatigue	1.8	Trailing edge	
	140.5	Damage			
	160.2	S-R cracks	2.3	Midchord	
Av. life:	100				
7	33.5	S-R cracks	1.8	Midchord	Inserted at 50 hr[c]
	64.7		2.3	Leading edge	
	64.7		2.0	Midchord	
	64.7		2.2		
	99.0		2.0		
	103.7		2.1		50 hr
	139.0		2.2		Inserted at 50 hr
	145.7		2.8		50 hr
Av. life:	89				
8	91.3	S-R cracks	3.0	Midchord	125.8 hr
	112.2	Fatigue	1.7	Trailing edge	83.5 hr
	114.5	S-R cracks	2.8	Leading edge	74.5 hr
	121.2	S-R cracks	2.4	Midchord	Inserted at 74.5 hr
	126.8	S-R cracks	2.6	Midchord	90.2 hr
	135.6	Damage			64.7 hr
	144.0	Damage			74.5 hr
	167.2	S-R fatigue	3.0	Leading edge	99.0 hr
Av. life:	122				

[a]All buckets, vacuum-melted and air-melted, had thermal-fatigue cracks on leading edges at time of failure.

[b]S-R cracks: stress-rupture cracking in airfoil; S-R fatigue: combination of stress-rupture and fatigue.

[c]Time when buckets were introduced into test refers to rated-speed time accumulated in test from its inception; time to failure of these buckets is rated-speed time they were under test.

TABLE IV. - OCCURRENCE OF LEADING-EDGE CRACKS IN GMR 235 BUCKETS[a]

Condition	Group	Accumulated time at inspection, hr											
		24.2			38.0			50.0			74.5		
		Starts at inspection											
		7			10			12			21		
		Number cracks in airfoil	Location above base platform, in.	Severity (b)	Number cracks in airfoil	Location above base platform, in.	Severity (b)	Number cracks in airfoil	Location above base platform, in.	Severity (b)	Number cracks in airfoil	Location above base platform, in.	Severity (b)
Vacuum melted	1	0			(c)	2.2-2.5	s	13	1.9-2.5	s	12	1.5-2.5	s
		0			1	2.3	x	(c)	2.1-2.3	s	7	1.3-3.1	x
		0			0			0			12	1.5-2.6	x
		(c)	2.1	s	0			(c)	1.9-2.3	s	8	1.4-1.8	x
		(c)	2.1	s	0			↓	2.0	s	0		
		0			(c)	2.0-2.6	s	↓	2.3	s	10	1.2-2.2	s
		0			0			6	2.2-2.5	x	5	2.3-2.7	x
		0			(c)	2.4-2.5	s	5	1.0-2.8	s	9	1.2-2.5	x
	2	0			0			0			0		
		↓			(c)	1.9-2.8	s	0			6	1.2-2.4	x
		↓			0			--	1.1	s	7	1.2-2.5	s
		↓			(c)	2.0-2.5	s	4	2.3-2.5	s	10	1.2-2.5	s
		↓			-	2.0	s	0			0		
		↓			0			↓			5	1.0-2.5	s
		↓			0			↓			15	1.1-2.5	x
		↓			(c)	2.1-2.5	s	↓			18	1.2-2.6	x
	3	(c)	1.9-2.6	s	7	1.6-2.9	x	(d)	1.5-2.2	s	10	1.2-3.5	x
		↓	1.8-2.5	s	5	1.9-2.3	x	0			25	1.2-3.1	x
		↓	1.8-2.6	s	0			6	1.5-2.6	x	1	2.1	x
		↓	1.5-2.8	s	(c)	2.0-2.6	s	5	1.9-2.5	x	10	1.5-2.5	x
		↓	2.1-2.2	s	↓	1.9-2.4	s	0			10	1.2-2.8	s
		0			↓	1.9-2.4	s	8	2.0-2.4	x	12	1.8-2.8	x
		0			↓	2.1-2.6	s	1	2.7	s	2	2.5-2.6	x
		(c)	2.1-2.5	s	4	2.0-2.3	x	3	2.0-2.4	x	12	1.8-2.9	x
	4	0			2	2.3-2.5	x	3	2.1-2.4	x	6	2.2-2.5	x
		(c)	2.6	s	(c)	2.2-2.5	s	9	2.1-2.6	s	30	1.0-2.9	x
		0			5	1.9-2.8	x	5	2.0-2.4	s	16	1.5-2.8	x
		(c)	2.0	s	4	2.4-2.5	x	6	2.2-2.6	x	10	1.9-2.8	s
		0			(c)	2.5	s	15	1.9-2.6	s	16	1.5-2.8	s
		(c)	2.3-2.5	s	(c)	2.2-2.6	s	15	1.8-2.8	x	15	1.5-2.6	s
		0			0			6	2.6-2.8	x	6	2.2-2.8	s
		0			5	2.0-2.6	x	4	2.2-2.6	x	12	2.2-2.8	x
Air melted	5	0			(c)	2.4	s	7	1.5-2.6	y	Removed for metallographic study		
		↓			0			2	2.5	s	Removed at 64.7 hr as failed		
		↓			0			(c)	2.2-2.4	s	20	1.4-2.5	s
		↓			(c)	2.0-2.5	s	0			10	1.3-1.9	x
		↓			↓	2.6	s	0			5	1.4-2.9	x
		↓			↓	2.1-2.6	s	1	2.3	s	10	1.5-2.3	x
		↓			1	2.5	x	(c)	1.7-2.1	s	13	1.2-2.5	x
		↓			(c)	2.2-2.7	s	2	2.3-2.4	s	10	1.5-2.5	s
	6	(c)	1.3-2.7	s	(c)	1.9-2.6	s	50	1.1-1.5	y	15	1.2-3.1	y
		↓	1.7-2.5	s	1	1.9	x	4	1.7-2.7	x	10	1.2-2.9	y
		↓	1.9-2.1	s	0			(c)	1.8-2.6	s	(e)		
		↓	1.8-2.5	s	(c)	1.7-2.9	s	Removed at 50 hr, reinserted at 64.7 hr, failed at 84.3 hr					
		0			0			2	1.8-2.4	s	(f)		
		(c)	1.9-2.5	s	2	2.2-2.5	x	(c)	2.2-2.5	s	10	1.6-2.6	x
		↓	2.0-2.5	s	(c)	2.3-2.4	s	1	2.3	x	10	1.4-2.8	z
		↓	1.9-2.2	s	5	2.0-2.8	x	1	2.5	s	15	1.4-2.6	x
	7	0			1	2.2	x	3	1.2-2.5	x	Failed at 64.7 hr, SR-F		
		↓			(c)	2.2	s	0		-			
		↓			↓	2.2-2.8	s	1	2.5	s	7	2.0-2.5	x
		↓			↓	2.0-2.6	s	2	2.2-2.7	s	Failed at 64.7 hr, SR		
		↓			-	Failed at 33 hr, inserted at 50 hr accumulated in test[g]							
		↓			0			0			12	1.5-2.5	s[g]
		↓			0			0			0		
		↓			0			1	1.9	x	6	1.9-2.5	x[g]
	8	0			0			0			0		
		↓			↓			↓			0		
		↓			↓			↓			8	1.0-2.0	x[g]
		↓			↓			↓			0		
		↓			↓			↓			7	1.8-2.5	s[g]
		↓			↓			↓			0		
		↓			↓			10	2.1-2.8	s	5	2.0-2.2	s[g]
		↓			↓			0			10	2.2-2.7	s[g]

[a]Fatigue cracking not detected at first inspection after 10 hr and 4 starts. First cracks detected after 24.2 hr, as table data show.

[b]Symbols defined as follows:
- s   indications so small as to be considered only a little better than suspicion of cracks
- x   definite cracks <1/32 in. long
- y   crack length 1/32 in. to 1/16 in.
- z   crack length >1/16 in.
- SR   stress-rupture
- SR-F   stress-rupture plus fatigue

[c]Impractical to count because of fineness of indication of cracks.

[d]Impractical to count because scaling of alloy obliterated majority of cracks.

[e]Damaged at 50 hr; no additional readings taken; failed by stress-rupture fatigue at 74.5 hr.

[f]Removed at 50 hr; reinserted at 64.7 hr; failed at 106.1 hr.

[g]Inserted into wheel as replacement buckets at times indicated. Inspection times indicated are approximate in order not to complicate table.

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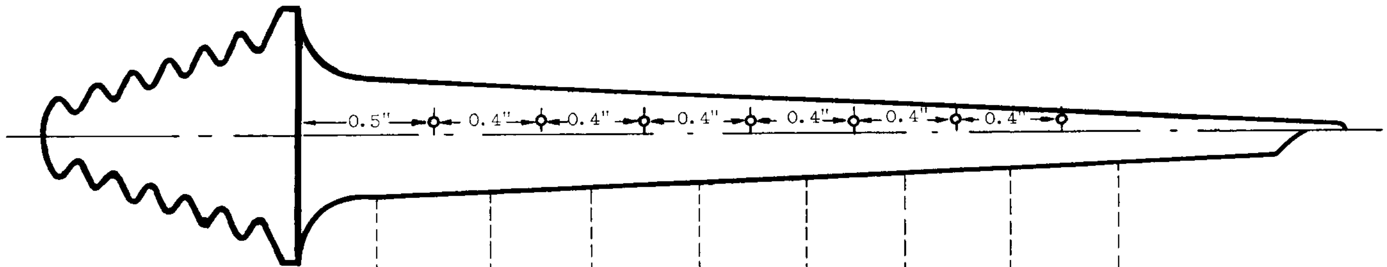
TABLE IV. - Concluded. OCCURRENCE OF LEADING-EDGE CRACKS IN GMR 235 BUCKETS

Condition	Group	Accumulated time at inspection, hr															
		99.0			120.8			160.2			195.7			230.2			268.6
		Starts at inspection															
		28			31			42			54			78			100
		Number cracks in airfoil	Location above base platform, in.	Severity (a)	Number cracks in airfoil	Location above base platform, in.	Severity (a)	Number cracks in airfoil	Location above base platform, in.	Severity (a)	Number cracks in airfoil	Location above base platform, in.	Severity (a)	Number cracks in airfoil	Location above base platform, in.	Severity	
Vacuum melted	1	20	1.5-2.5	s	30	1.4-3.2	x	Removed						Inspected at 230.2 and 268.6 hr Cracks obliterated by oxide scale			
		0			20	1.7-3.0	s	Removed									
		12	1.5-2.6	x	10	2.0-2.8	s	12	1.5-2.5	s	(b)	-------	--				
		20	1.4-3.0	s	40	1.1-3.0	s	10	1.7-2.7	x	(b)	-------	--				
		0			7	1.9-2.5	x	10	1.5-2.5	x	10	1.5-2.5	y				
		15	1.2-2.8	s	(b)	0.7-3.3	x	0			10	1.5-2.5	x				
		15	1.2-3.0	x	40	1.0-2.2	s	4	2.3-2.5	s	(b)	-------	--				
		0			12	1.9-3.1	x	10	1.8-2.8	x	(b)	-------	--				
	2	(c)	1.0-2.5	s	30	1.2-3.0	s	5	1.6-2.6	x	20	1.6-2.8	z				
		12	1.6-2.8	x	15	2.6-2.8	s	6	1.5-2.4	s	20	1.3-3.0	s				
		(b)	1.3-2.5	s	10	1.4-2.5	s	6	1.8-2.5	x	(b)	-------	--				
		0			15	1.7-3.0	s	10	1.7-2.5	s	10	1.1-3.0	s				
		0			6	2.0-2.2	s	3	1.7-2.0	s	30	1.1-3.0	x				
		3	2.2-2.3	s	10	1.2-2.9	s	15	1.5-2.8	x	(b)	-------	--				
		(b)	1.1-2.5	s	16	1.3-2.1	x	5	1.1-3.0	s	25	1.1-3.0	x				
		0			20	1.2-3.2	s	0			20	1.0-3.0	x				
	3	(b)	1.2-2.8	s	(b)	1.0-3.0	y	Failed									
		(b)	-------	--	↓	1.0-3.0	s	(b)	-------	--							
		30	1.2-2.8	x	↓	1.2-3.4	s	↓	-------	--							
		(b)	-------	--	↓	1.5-2.9	s	↓	-------	--							
		20	1.2-3.0	x	↓	1.3-3.1	s	↓	-------	--							
		20	1.8-3.0	x	↓	1.2-3.0	s	↓	1.6-2.8	--							
		12	1.6-2.[illegible]	x	↓	1.1-3.2	x	12	1.5-3.0	x							
		12	1.8-3.0	y	30	1.1-2.9	y	(b)	2.5-	y	(b)	2.5	y				
	4	8	2.0-3.0	x	30	1.4-3.0	x	(b)	-------	--							
		15	2.1-2.8	x	25	0.8-3.1	x	15	1.5-2.5	y							
		16	1.5-2.8	x	30	1.4-2.8	x	20	1.6-2.8	y							
		20	1.5-3.2	x	15	2.1-3.1	s	8	2.1-2.5	s							
		0			10	2.0-2.6	s	12	1.5-2.8	s							
		15	1.5-2.6	s	15	1.9-2.8	x	15	1.7-3.0	s							
		15	1.8-2.8	s	40	1.0-2.1	s	0									
		15	2.0-2.8	x	30	1.2-2.9	s	15	1.5-3.0	x							
Air	5	Removed for metallographic study															
		Removed at 74.[illegible] hr as failed															
		Removed at 74.5 hr as failed															
		30	1.2-2.8	x	Removed at 99 hr as failed												
		6	1.4-2.9	s	Removed at 99 hr as failed												
		12	1.5-2.8	y	Removed at 99 hr as failed												
		13	1.2-2.5	x	Removed at 99 hr as failed												
		20	1.2-3.0	y	30	1.1-3.0	y	Removed at 120.8 hr as failed									
	6	Removed at 74.5 hr as failed															
		Removed at 74.5 hr as failed															
		Damaged at 50 hr, no additional readings taken, failed by SR-F at [illegible]4.5 hr															
		Removed at 50 hr, reinserted at 64.7 hr, failed at 84.5 hr															
		Removed at 50 hr, reinserted at 64.7 hr, failed at 106.1 hr															
		15	1.4-3.0	x	(b)	1.2-3.0	x	Failed at 125.8 hr									
		20	1.1-3.1	z	30	1.0-2.9	1/8 in.	Failed at 140.5 hr									
		30	1.4-3.2	x	100	1.2-3.1	s	Failed at 160.2 hr									
	7	Failed at 64.7 hr, SR-F															
		Failed at 64.7 hr, SR															
		12	1.2-2.8	y	Failed at 99 hr, SR												
		Failed at 64.7 hr, SR															
		Failed at 33 hr, inserted at 50 hr accumulated in test[d]															
		Failed at 103.7 hr, inserted at 50 hr[d]															
		20	1.4-3.0	s	Failed at 139.0 hr, inserted at 50 hr[d]												
		30	1.5-3.0	1/16 in.	Failed at 145.7 hr, inserted at 50 hr[d]												
	8	Failed at 91.3 hr, inserted at 125.8 hr[d]															
		Failed at 112.2 hr, inserted at 74.5 hr[d]															
		Failed at 114.5 hr, inserted at 74.5 hr[d]															
					Failed at 121.2 hr, inserted at 74.5 hr[d]												
		15	1.0-3.0	x	Failed at 126.8 hr, inserted at 90.2 hr[d]												
		5	2.0-2.5	s	5	2.0-2.5	s	Failed at 135 hr, inserted at 64.7 hr[d]									
		0			20	1.1-2.5	x	Failed at 144 hr, inserted at 74.5 hr[d]									
		0			12	1.5-3.2	x	Failed at 167.2 hr, inserted at 99 hr[d]									

[a]Symbols defined as follows:
- s indications so small as to be considered only a little better than suspicion of cracks
- x definite cracks <1/32 in. long
- y crack length 1/32 to 1/16 in.
- z crack length >1/16 in.
- SR stress-rupture
- SR-F stress-rupture plus fatigue

[b]Impractical to count because scaling of alloy obliterated majority of cracks.
[c]Impractical to count because fineness of indication of cracks.
[d]Inserted into wheel as replacement buckets at times indicated. Inspection times indicated are approximate in order not to complicate table.

TABLE V. - ROCKWELL C HARDNESS OF NEW AND OPERATED GMR 235 BUCKETS



								Av.
Group 1:								
New	29	30	30	31.5	30.5	30	31	30.3
Operated 160.2 hr	34	32	34	31	31			
Operated 213.5 hr	33	34	34	32				
Group 2:								
New	30	29.5	28.5	29.5	30.5	--	28.5	29.4
Operated 230 hr	39	38	35	31	30	27		
Operated 268.6 hr	39	37.5	36	35	33	29.5	28	
Group 3:								
Operated 189 hr	36	37	33.5	31.5	32			
Operated 268.6 hr	40	37.5	34	32	31.5			
Group 4:								
New	29	31	32	31.5	32	32	31.5	31.3
Operated 160.2 hr	28	27	32.5	31	30	28	25	
Operated 268.6 hr	31.5	35	34	33	31	28	26	
Group 5:								
New	28	27	28	29	27.5	28	28.5	28.0
Operated 50 hr	33	35	32	31	31	29	31	
Operated 120 hr	30	31	31	33	31	31		
Group 6:								
Operated 74.5 hr	35	31	24	26	27.5	27	31	
Operated 160.2 hr	37.5	34	32	29.5				
Group 7:								
New	29.5	29	29	28.5	29	28	28.5	28.8
Operated 64.7 hr	36.5	32	28	24				
Operated 128 hr	25	31.5	26.5	30	27	21.5		
Group 8:								
New	28.5	29	29.5	29.5	28	32		29.4
Operated 91.3 hr	37	35	32	31	29	27		
Operated 167.2 hr	36	35	34	32	29	28.5		

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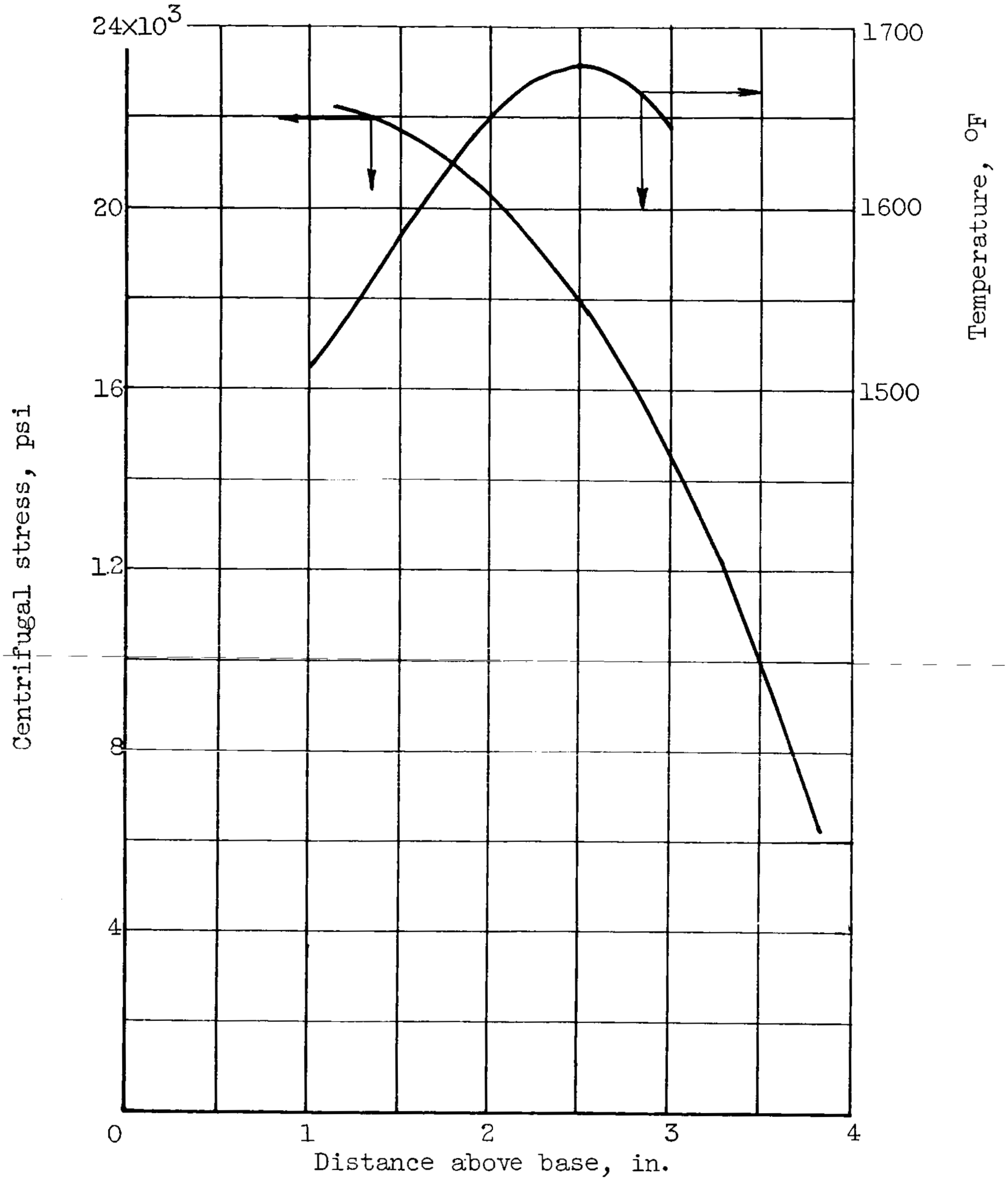


Figure 1. - Spanwise stress and temperature distributions in GMR 235 turbine buckets during rated-speed operation.

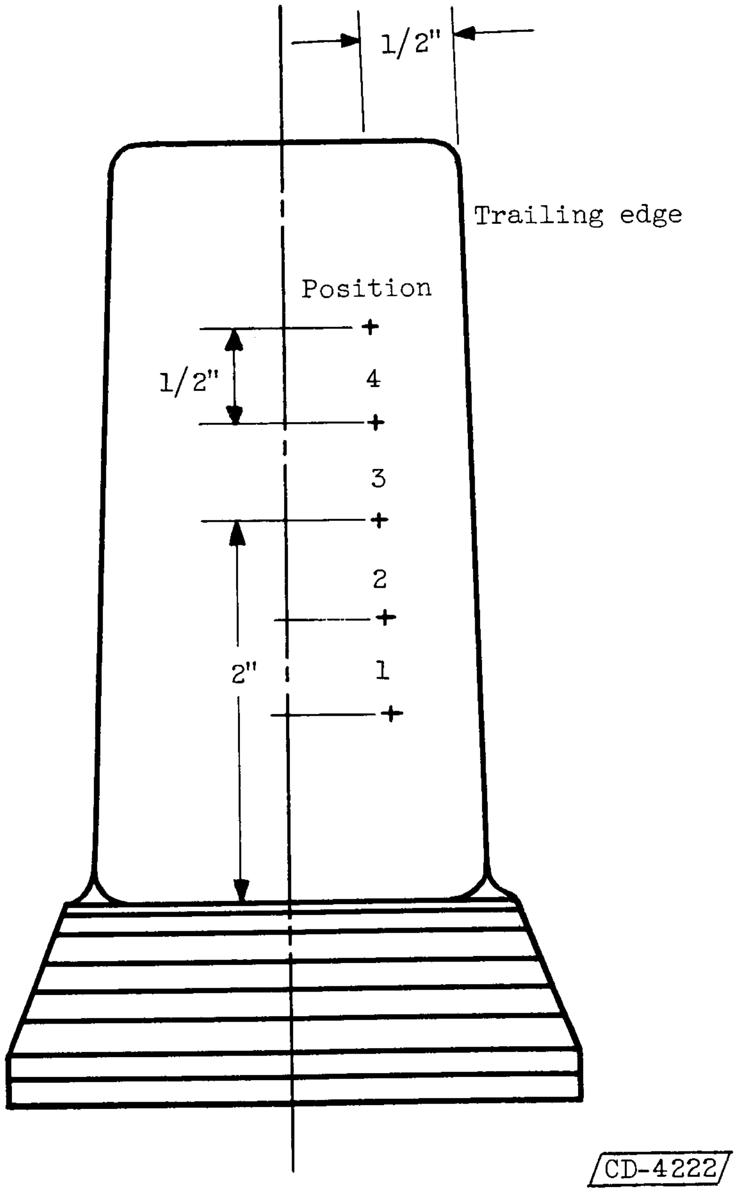


Figure 2. - Location of elongation gage marks on bucket airfoil.

E-559

CB-4

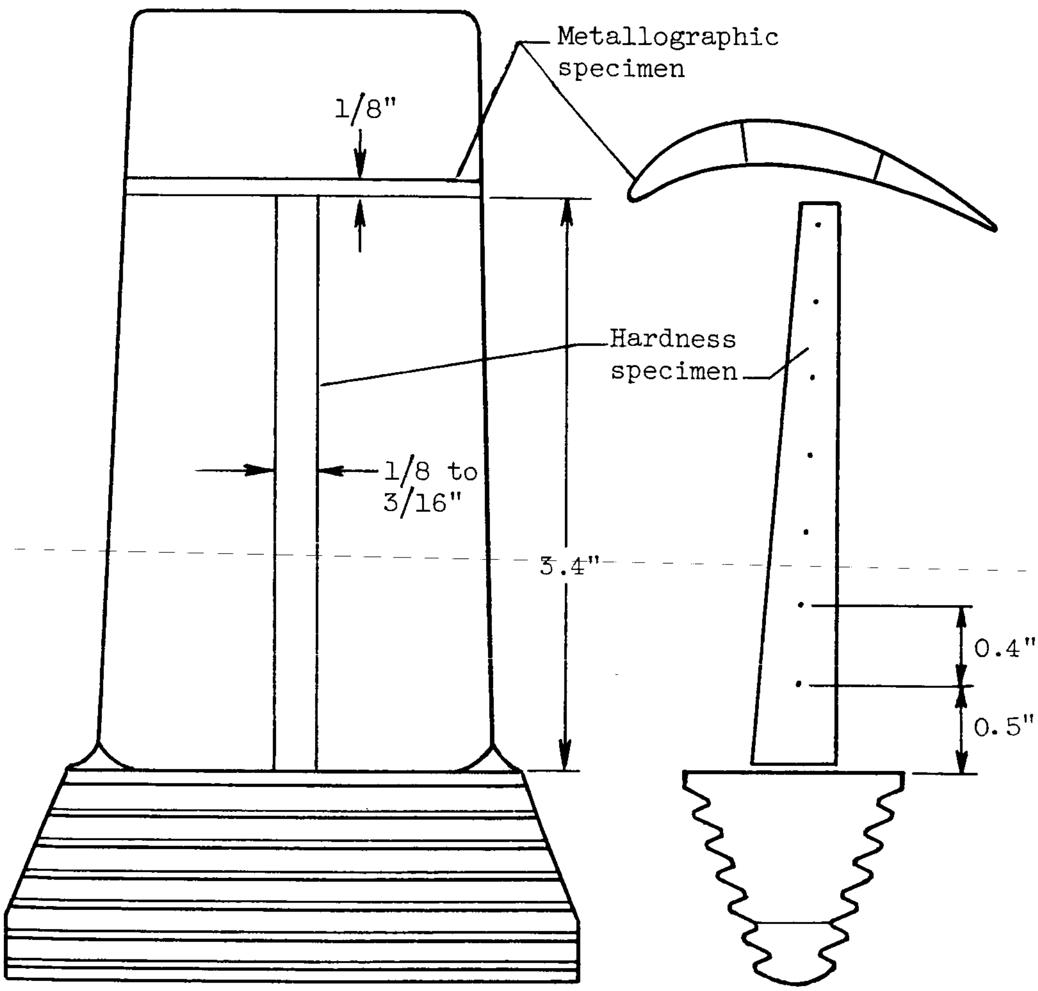


Figure 3. - Location of metallographic and hardness specimens.

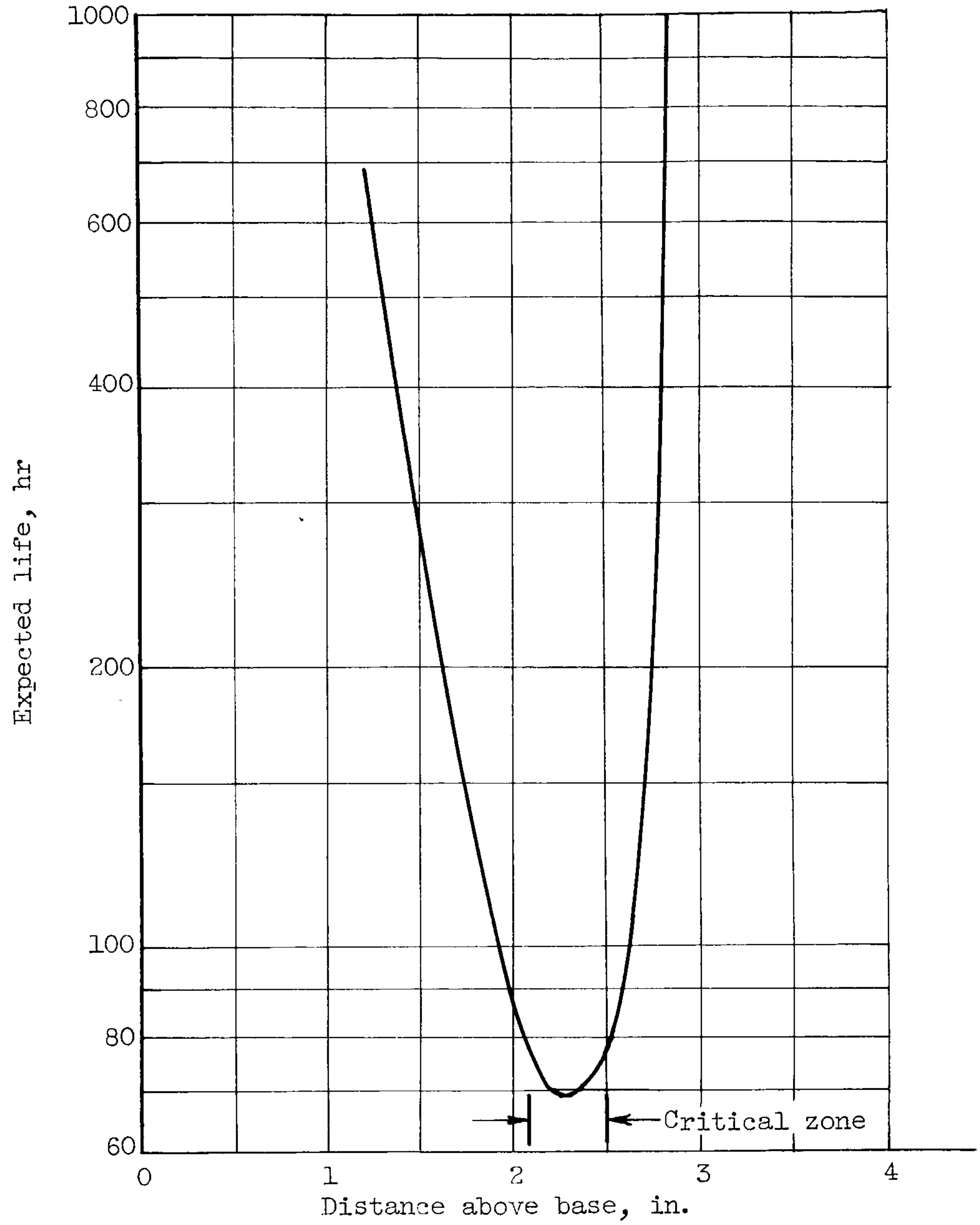
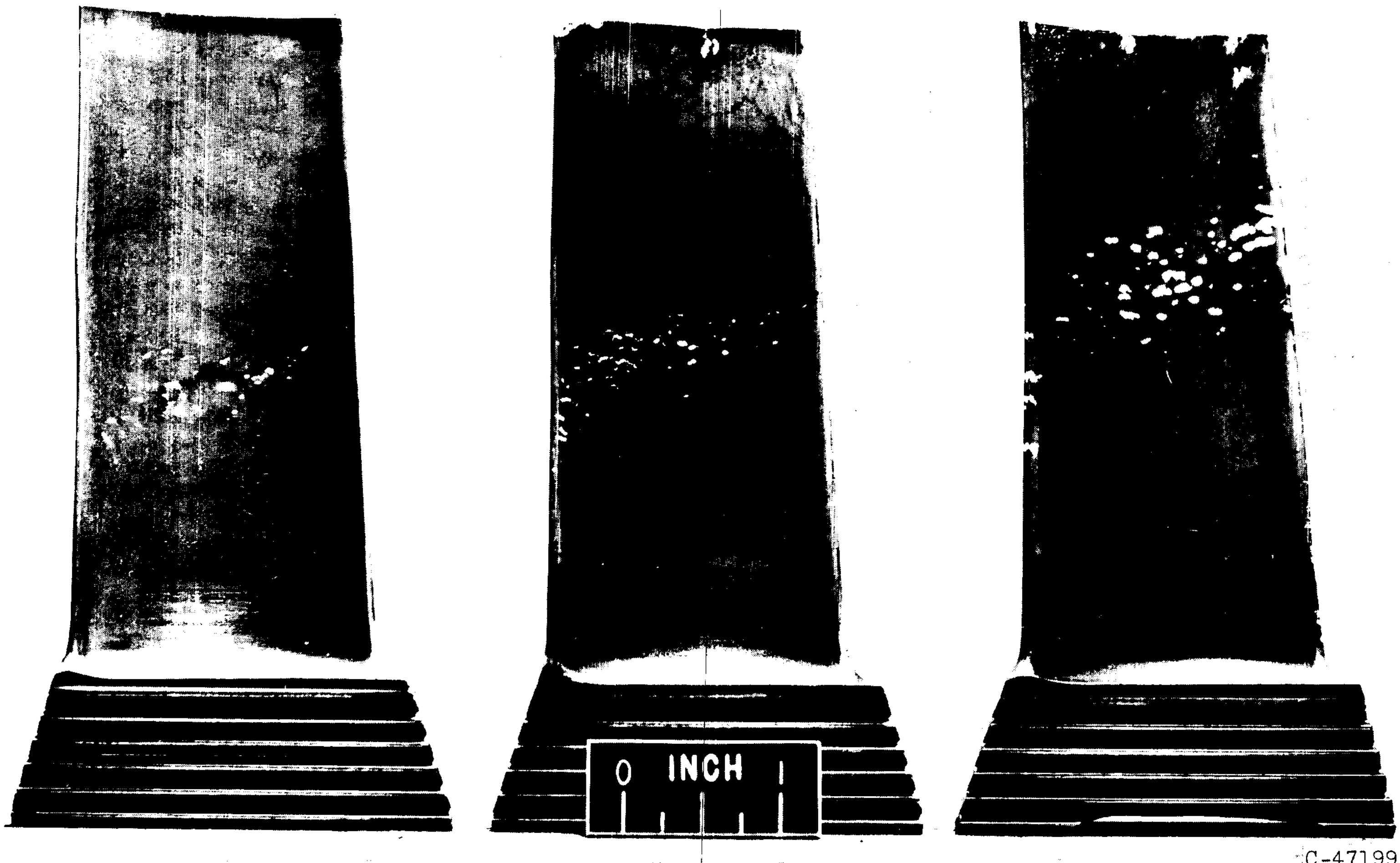


Figure 4. - Expected life of GMR 235 air-melted turbine buckets operating in J33-9 engine (based on manufacturer's stress-rupture data).

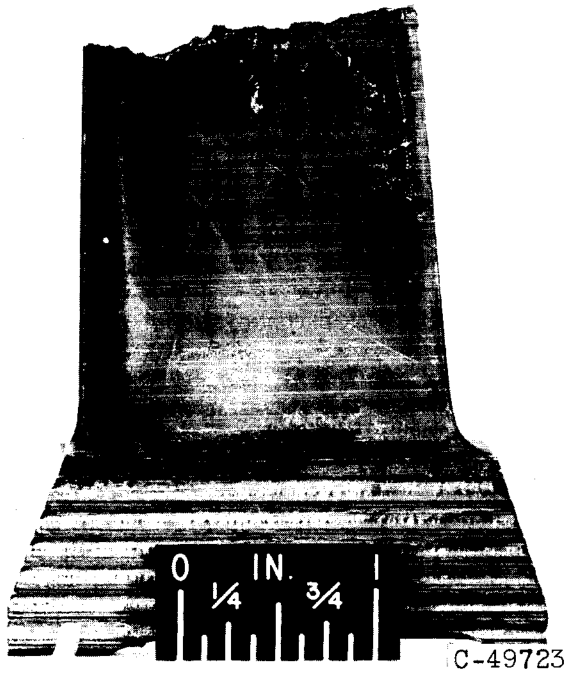


(a) Aluminized, group 8; considered failed at 114.5 hours of rated-speed operation.

(b) As-cast, group 5; considered failed at 99 hours of rated-speed operation.

(c) Aged, group 7; considered failed at 33.5 hours of rated-speed operation.

Figure 5. - Stress-rupture cracking occurring in airfoil of air-melted GMR 235 buckets.



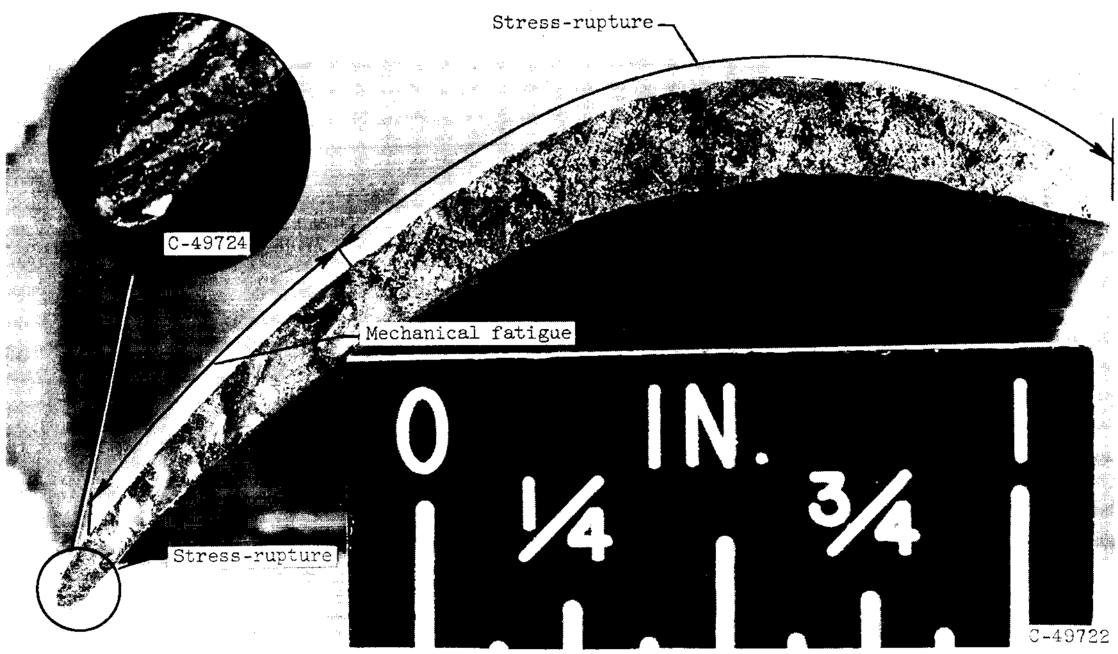


Figure 6. - Typical stress-rupture and mechanical-fatigue fracture. Air-melted diffusion-heat-treated group-6 bucket operated for 74.5 hours.

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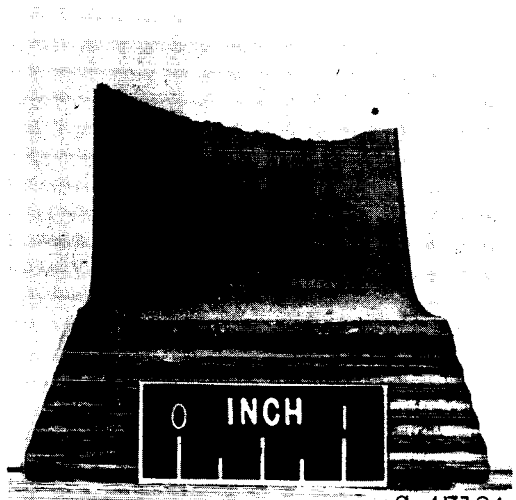


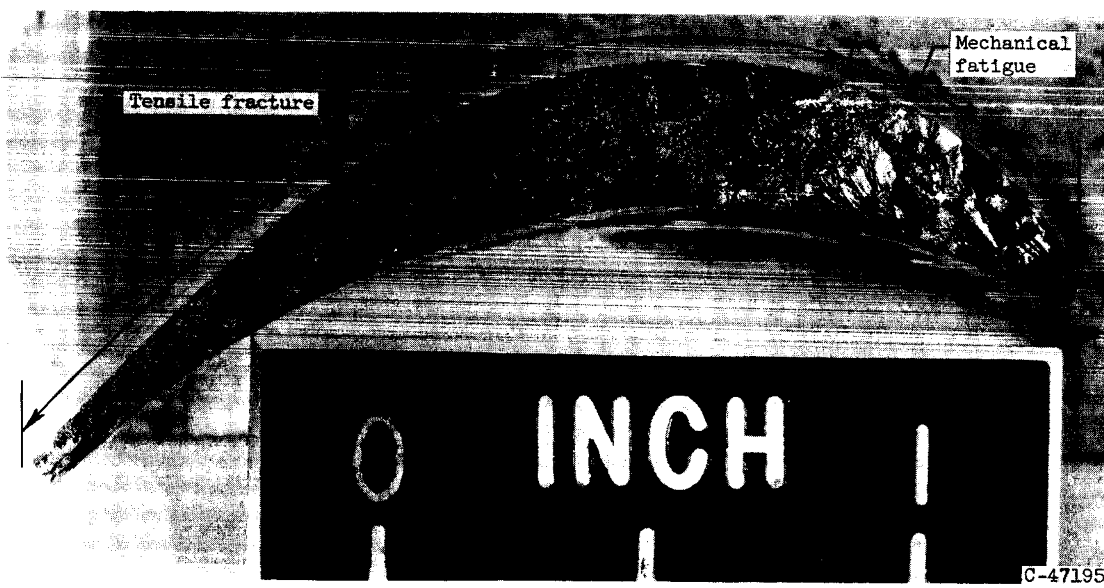
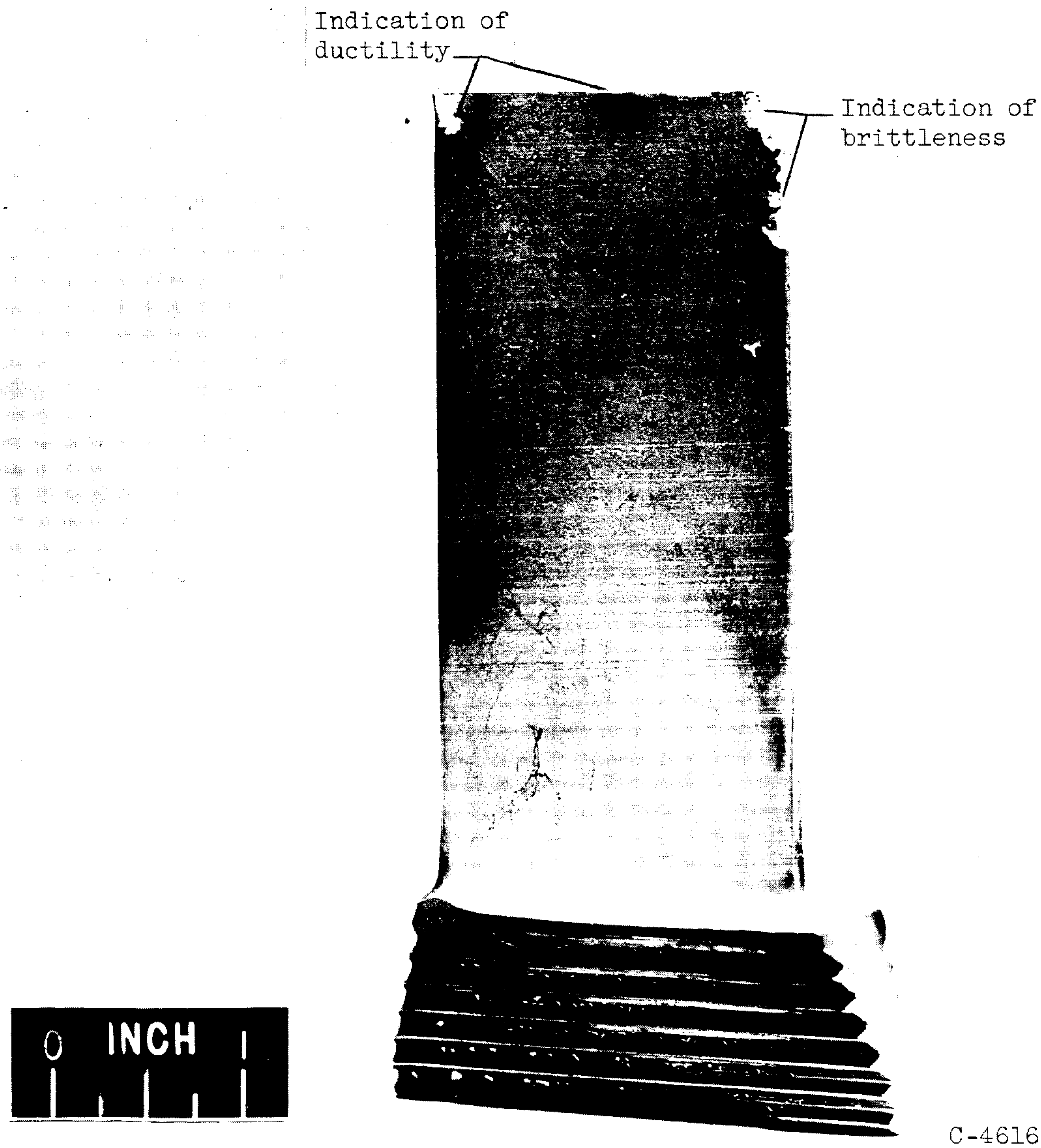


Figure 7. - Typical mechanical-fatigue fracture. Vacuum-melted aluminized group-2 bucket operated for 268.6 hours.



C-46165

Figure 8. - Damaged bucket indicating both brittleness and ductility to impaction by flying fragments.

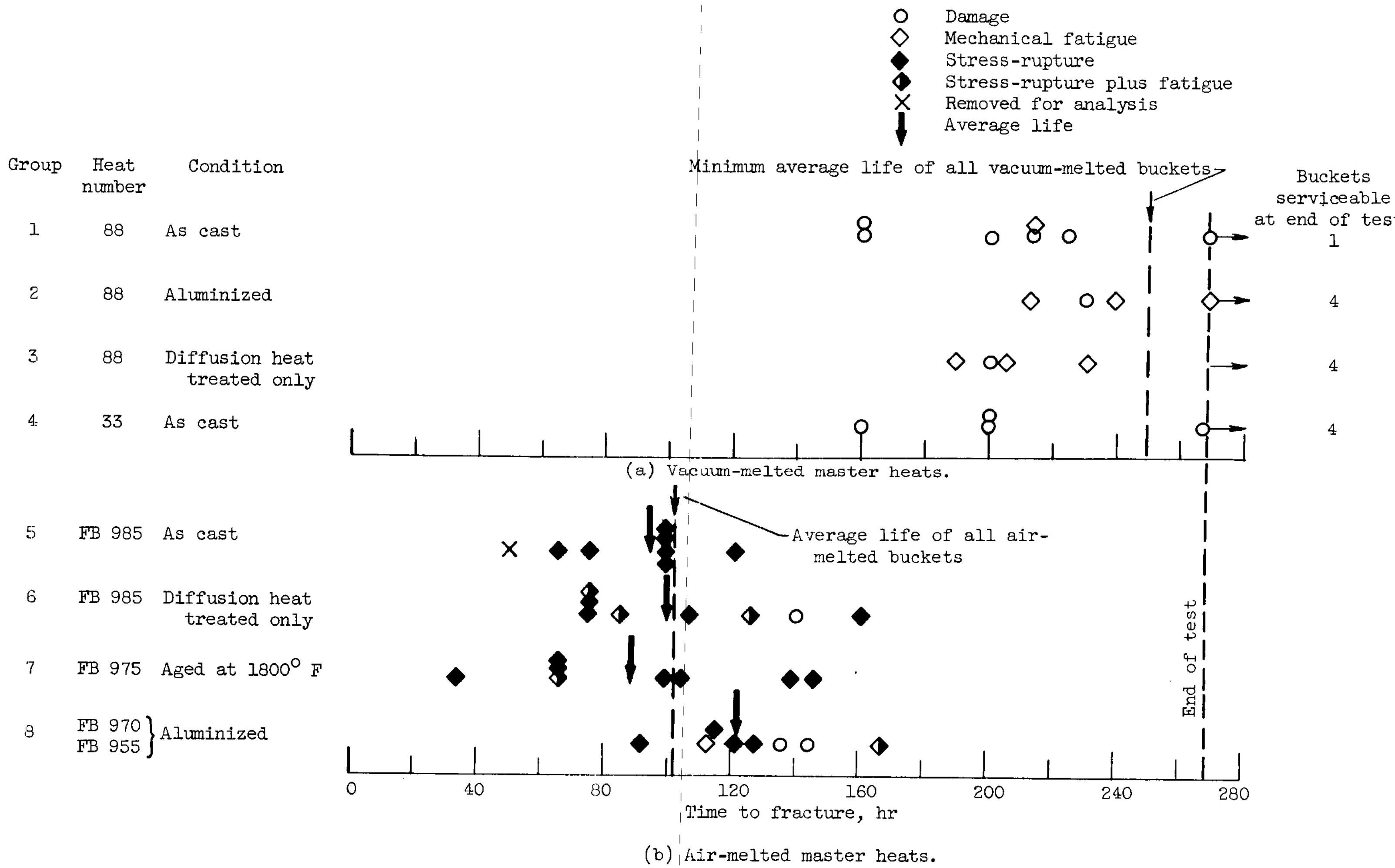
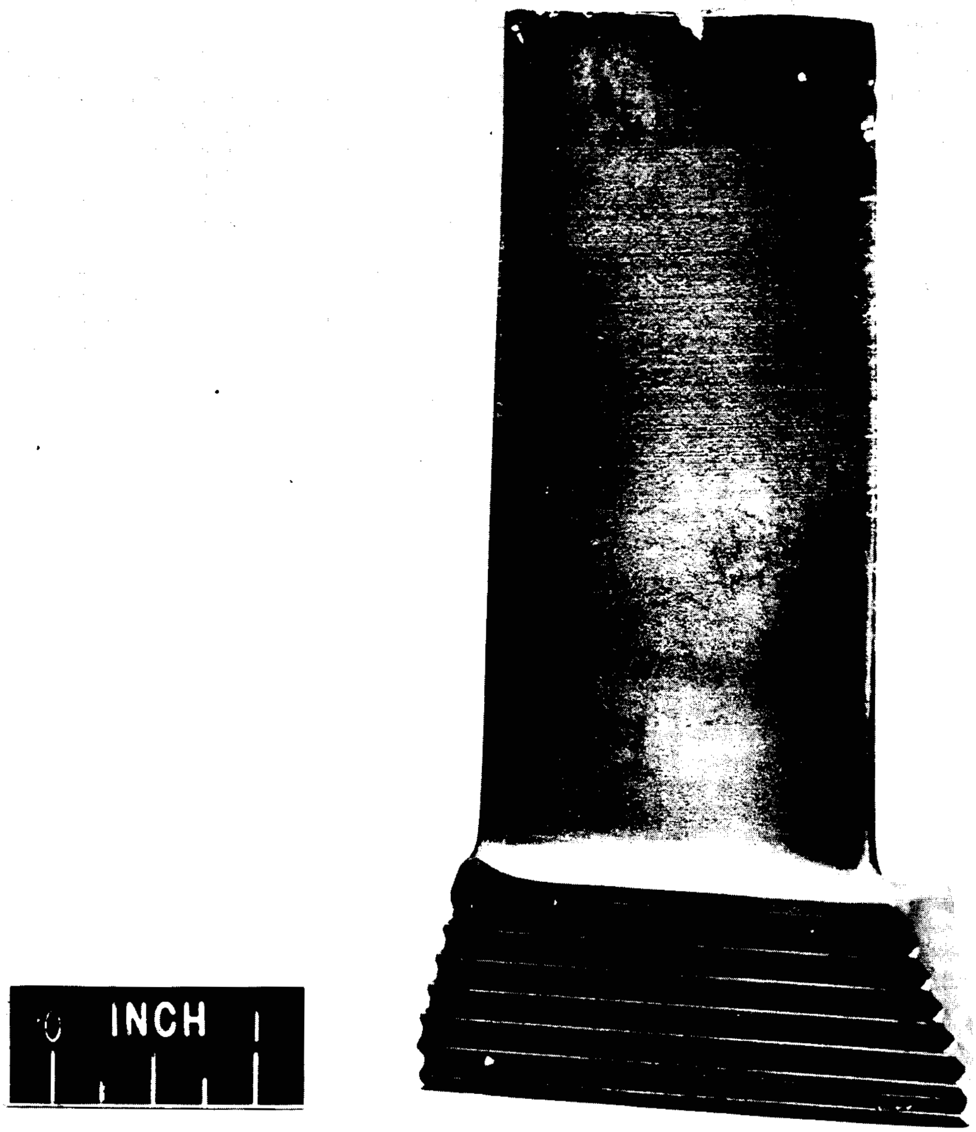


Figure 9. - Time to fracture of GMR 235 buckets in a J33-9 engine operating at 1650° F at rated speed (11,500 rpm).

E-559



C-46166

Figure 10. - Typical thermal-fatigue cracks developed in leading edges of GMR 235 buckets during operation.

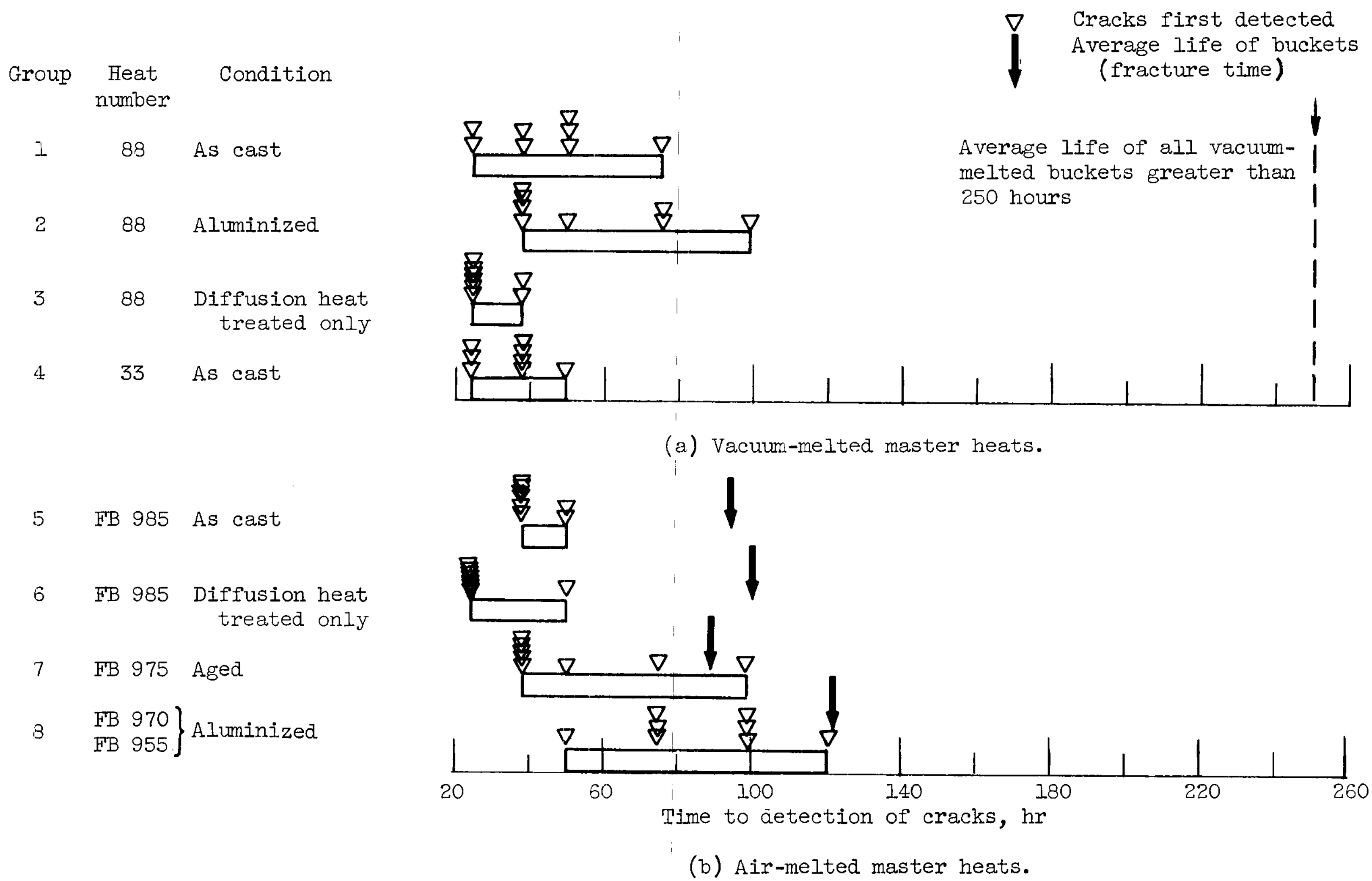
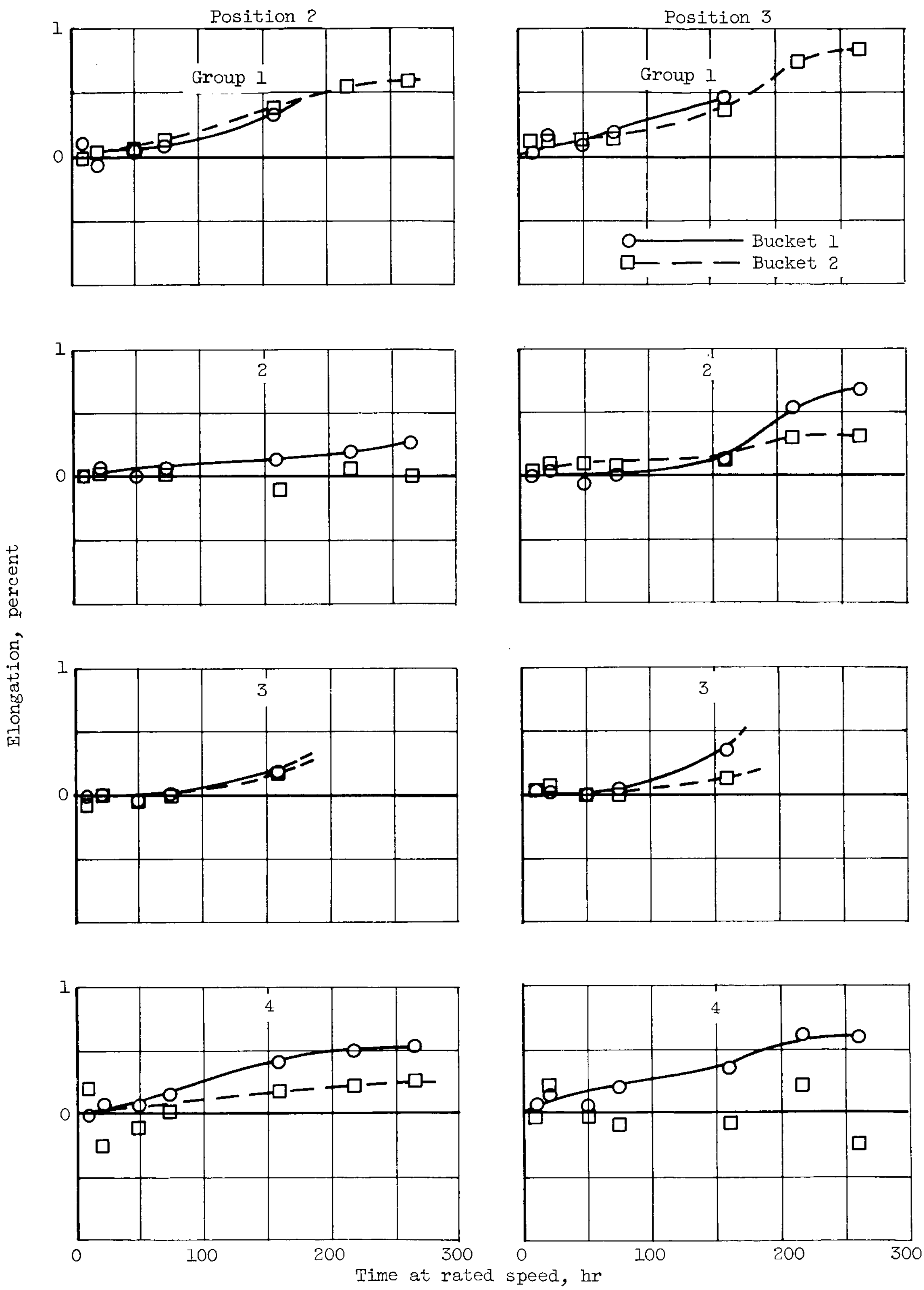


Figure 11. - Occurrence of thermal-fatigue cracks in GMR 235 buckets operated at 1650° F in a J33-9 turbojet engine, relative to average time to fracture.

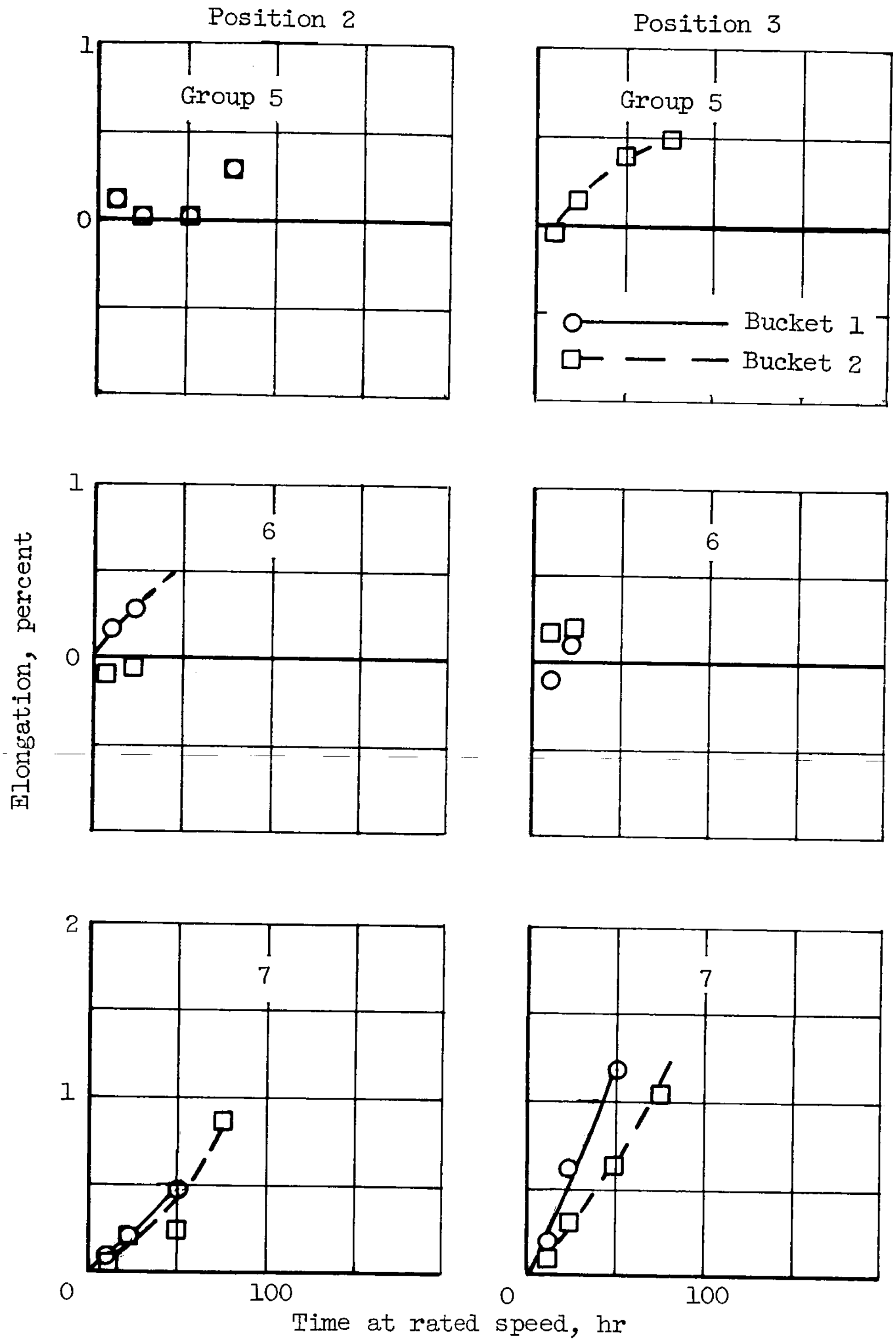


(a) Vacuum-melted buckets.

Figure 12. - Elongation of GMR 235 buckets during engine operation at 1650° F.

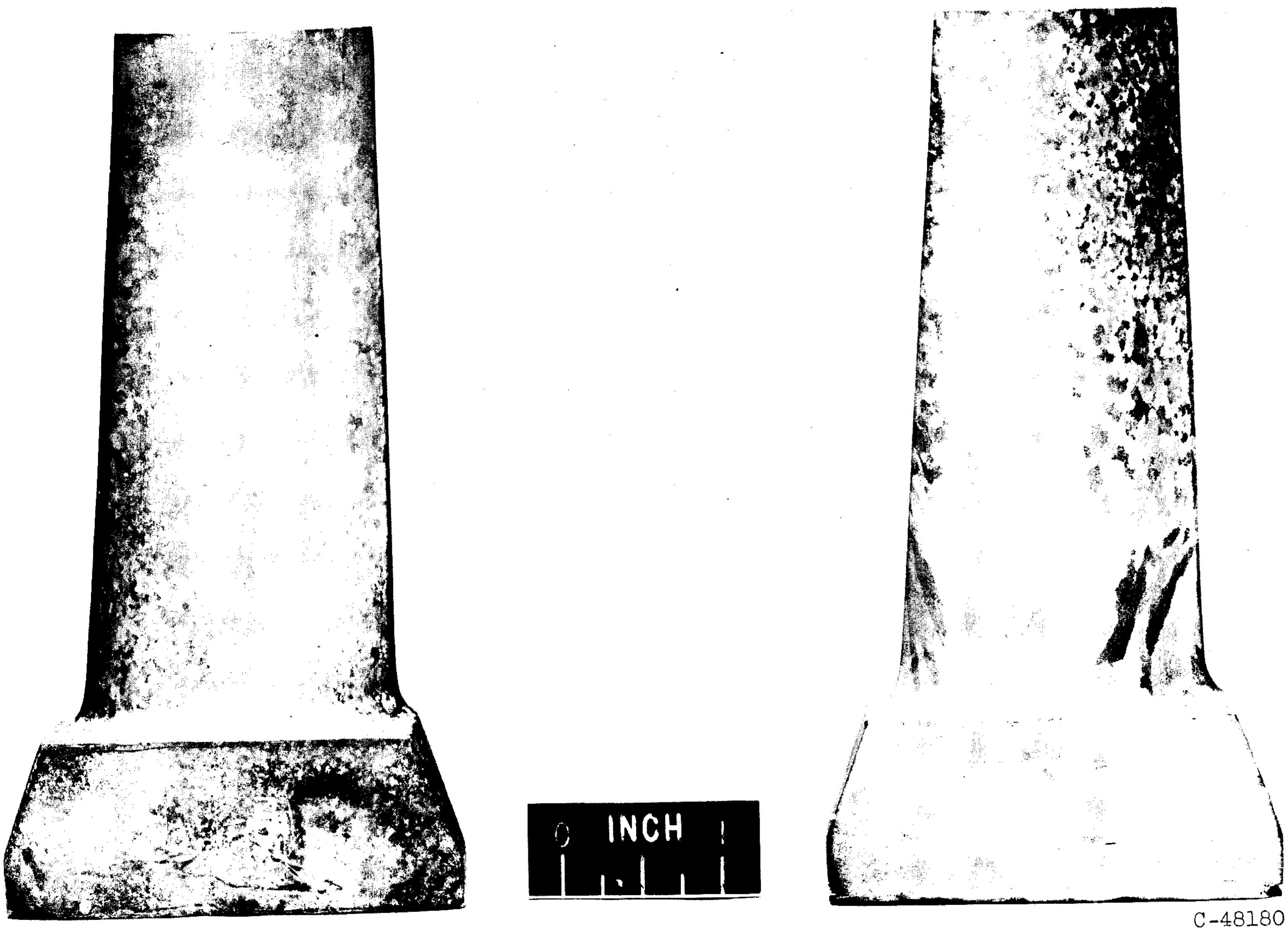
E-559

CB-5 back



(b) Air-melted buckets.

Figure 12. - Concluded. Elongation of GMR 235 buckets during engine operation at 1650° F.



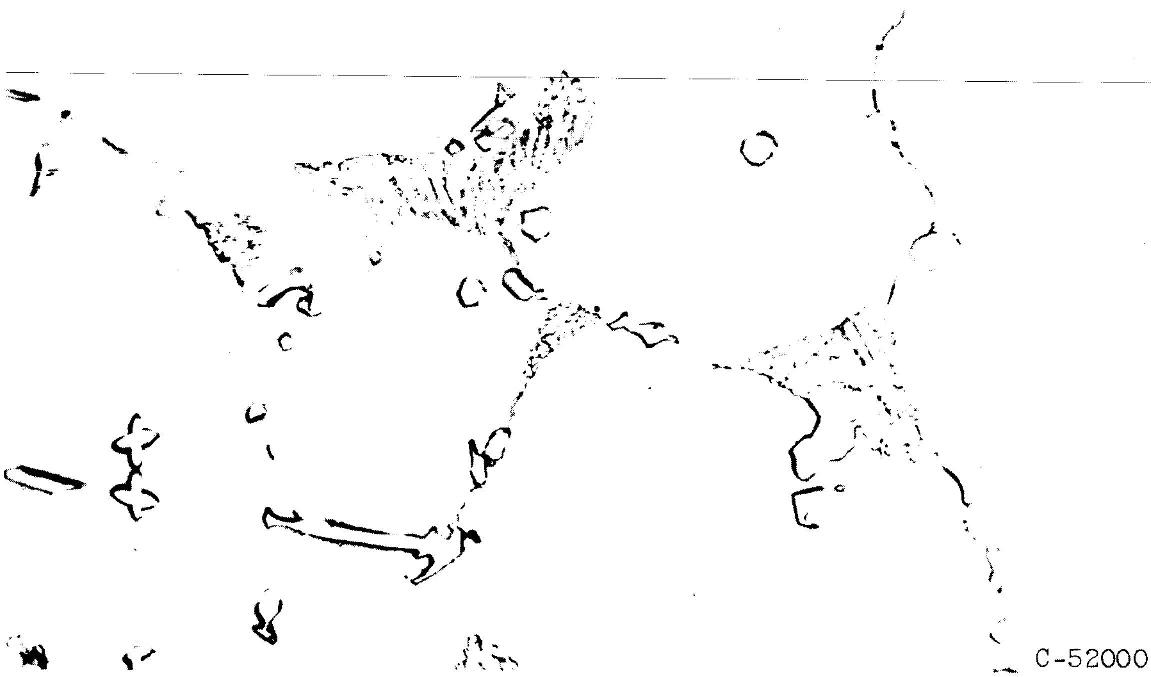
(a) Vacuum-melted bucket.

(b) Air-melted bucket.

Figure 13. - Macroetched as-cast buckets.

E-559

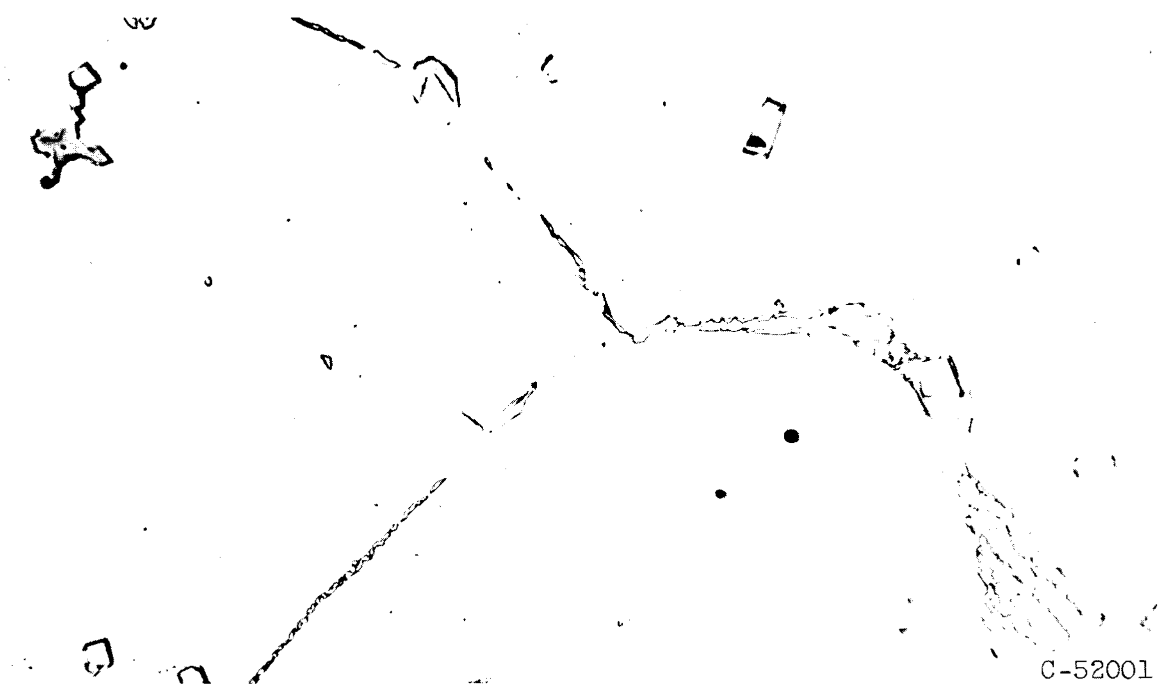
(a) As-cast vacuum-melted, group 1.



(b) Aluminized vacuum-melted, group 3.

Figure 14. - Typical microstructures of as-received GMR 235 buckets. Electrolytically etched in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X750.

(c) As-cast air-melted, group 5.



(d) Aluminized air-melted, group 8.

Figure 14. - Continued. Typical microstructures of as-received GMR 235 buckets. Electrolytically etched in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X750.

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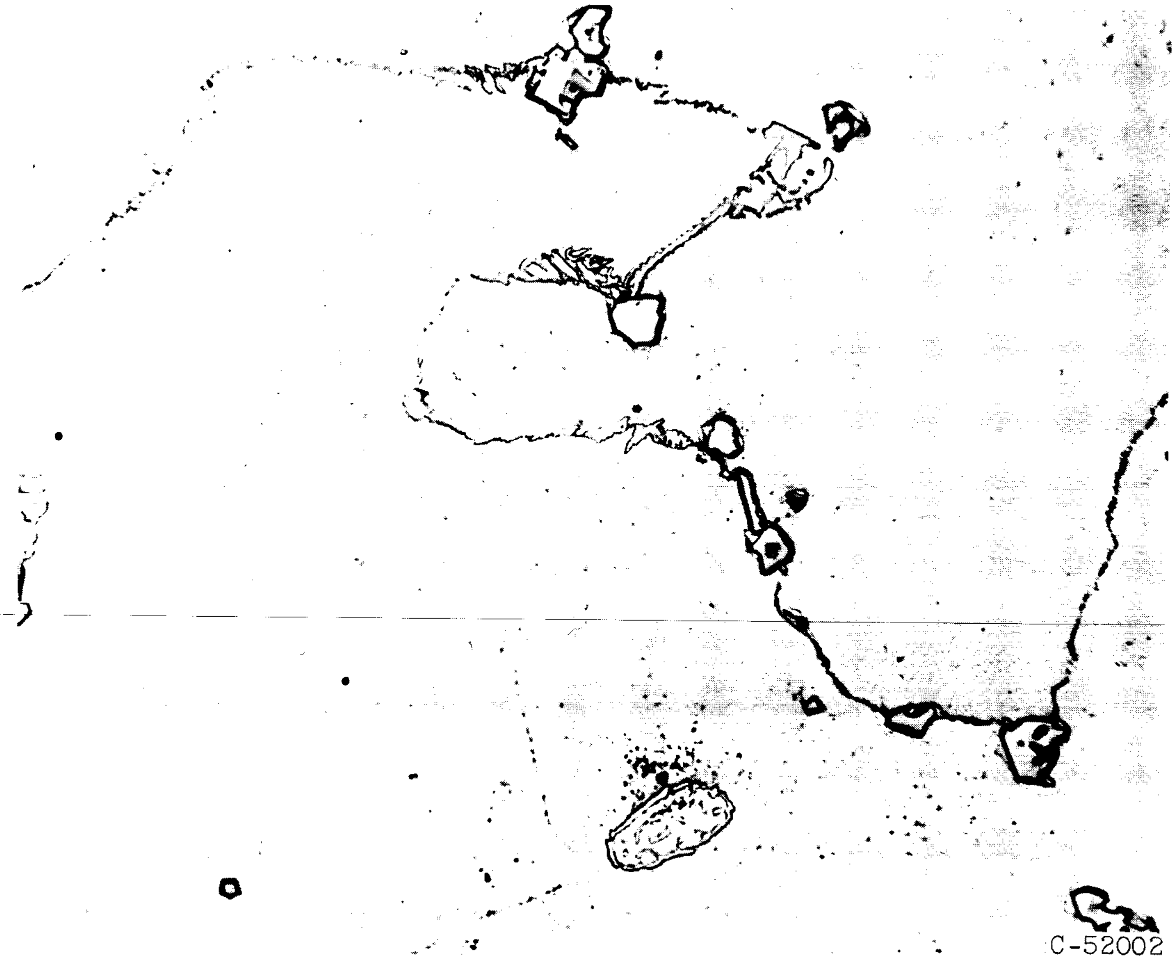


(e) Aged air-melted, group 7.

Figure 14. - Concluded. Typical microstructures of as-received GMR 235 buckets. Electrolytically etched in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X750.

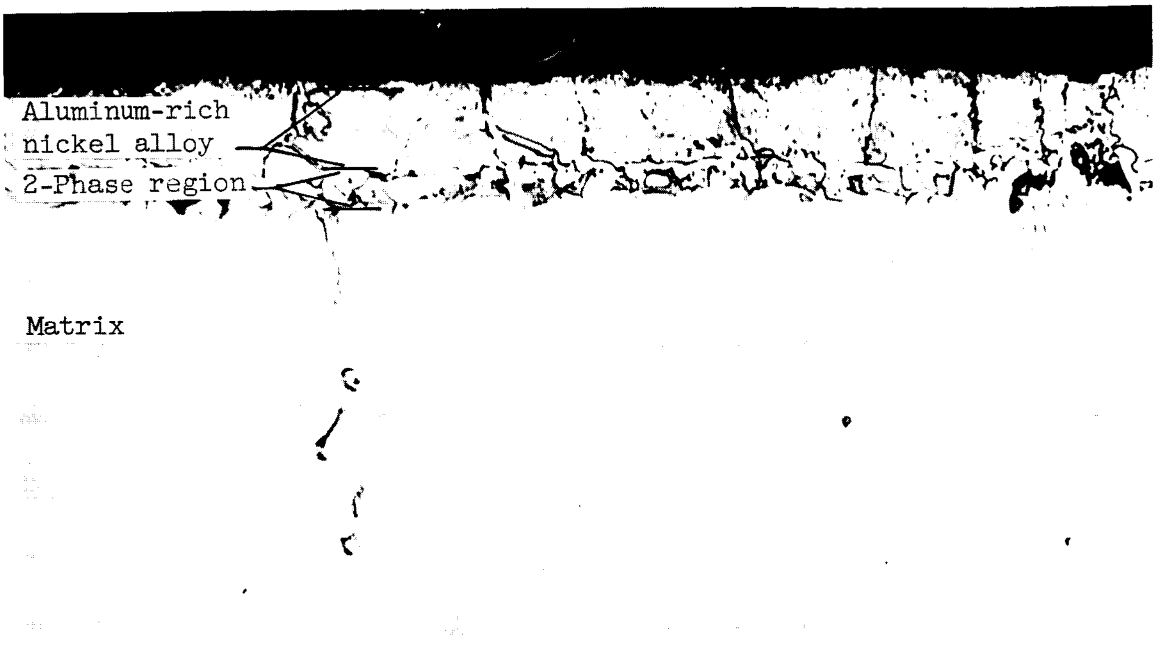
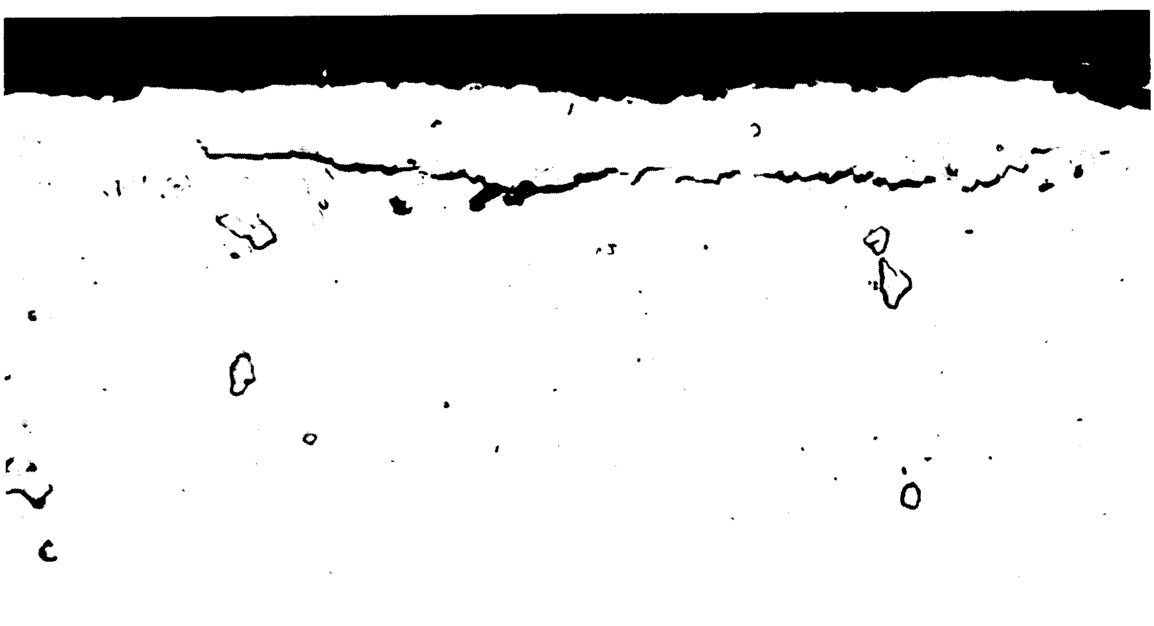


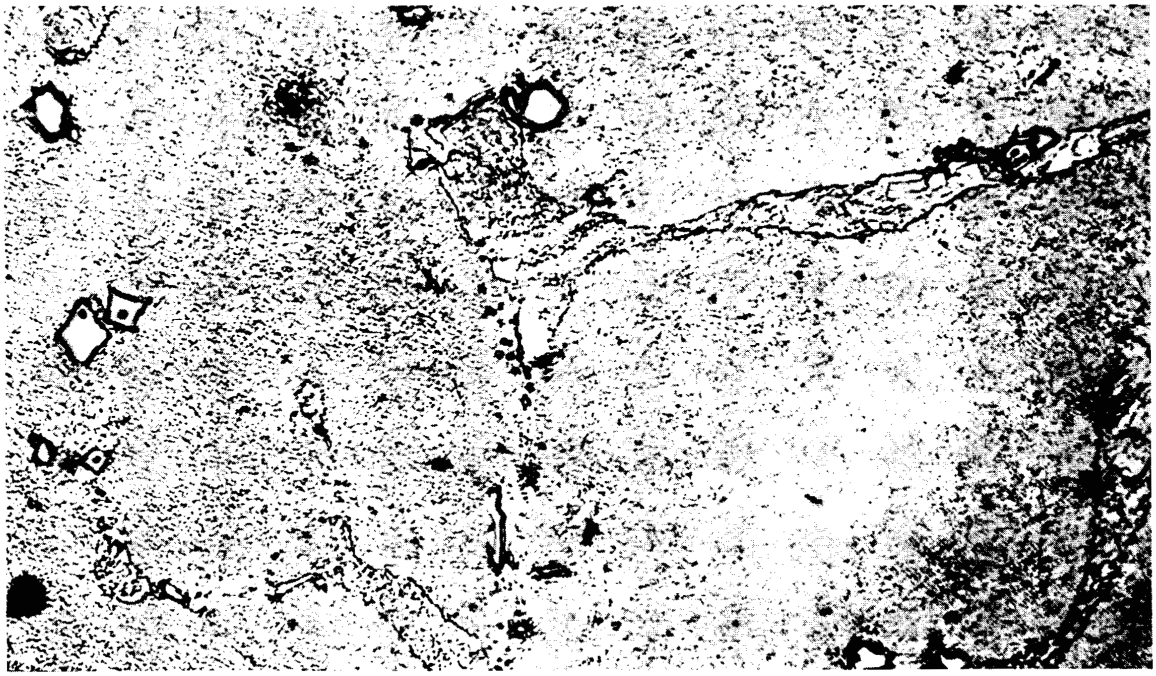
Figure 15. - Microstructure of coating present on aluminized buckets. Swab-etched with a 3-part glycerine, 2-part nitric acid, 1-part hydrofluoric acid solution; X1000.



C-52003

Figure 16. - Section of aluminized bucket showing crack in coating - base-metal interface. Unetched; X750.

E-559

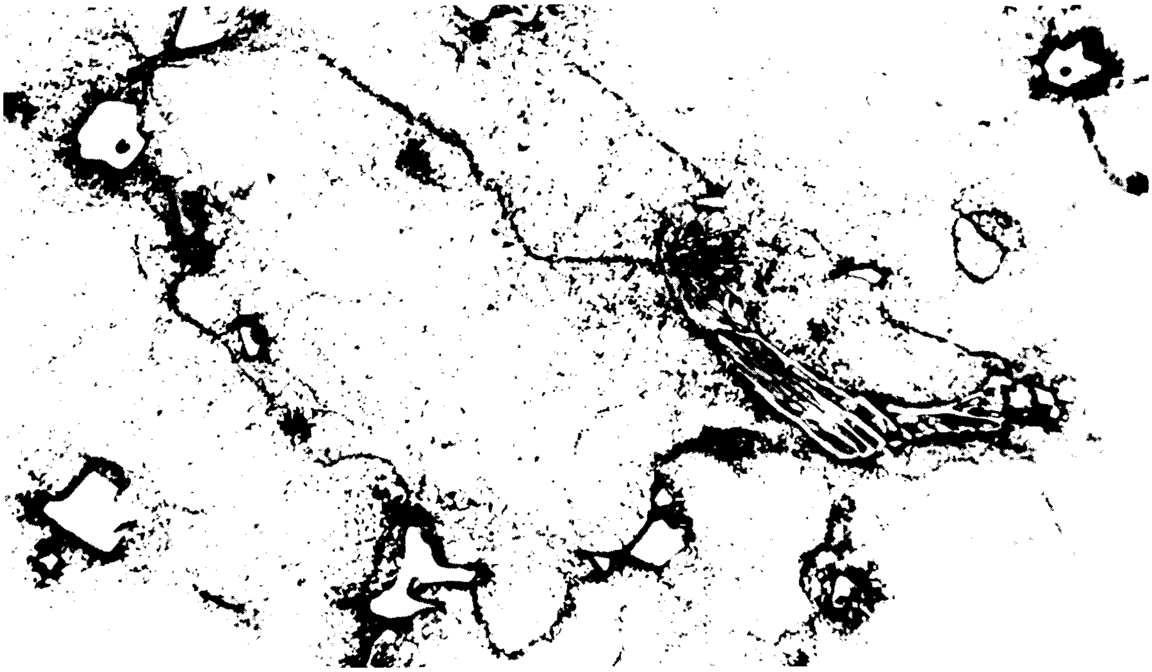


(a) As-cast vacuum-melted group-1 bucket operated 213.5 hours.

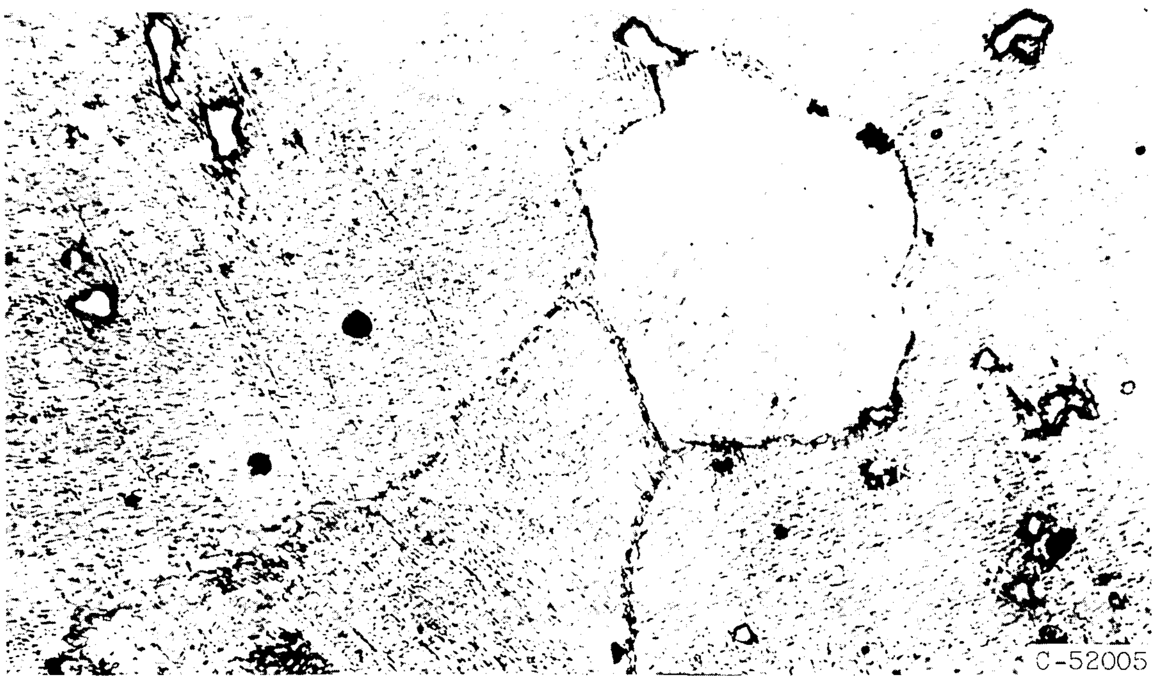
(b) Aluminized vacuum-melted group-2 bucket operated 212.5 hours.

Figure 17. - Typical microstructures of operated GMR 235 buckets. Electrolytically etched in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X750.

E-559

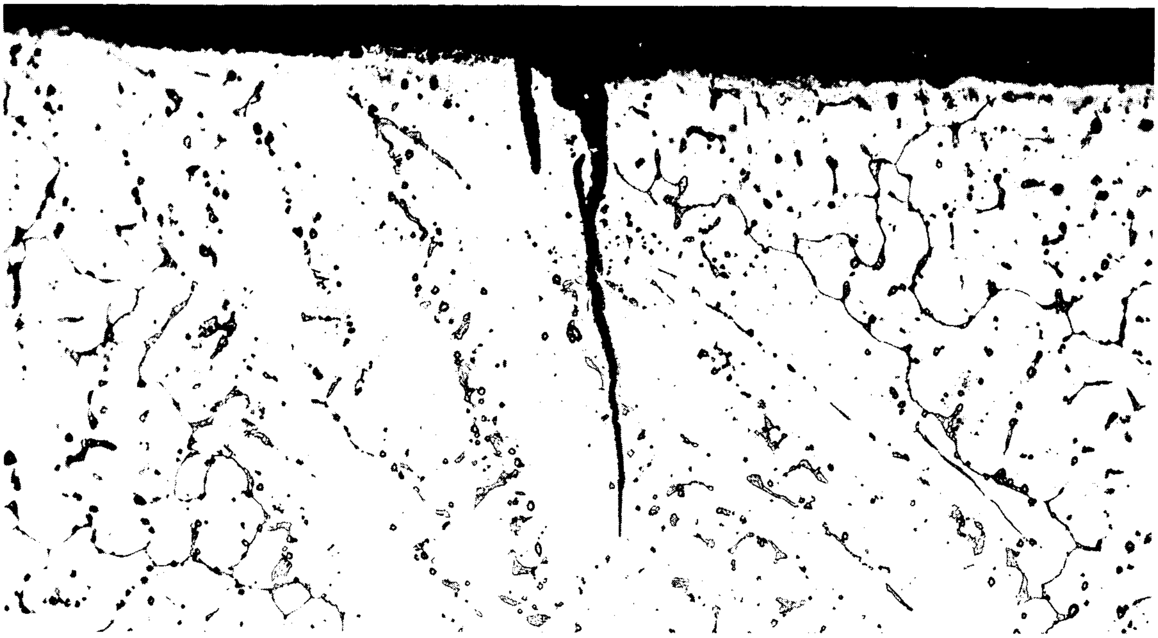


(c) As-cast air-melted group-5 bucket operated 120.8 hours. Note agglomeration of fine precipitates.

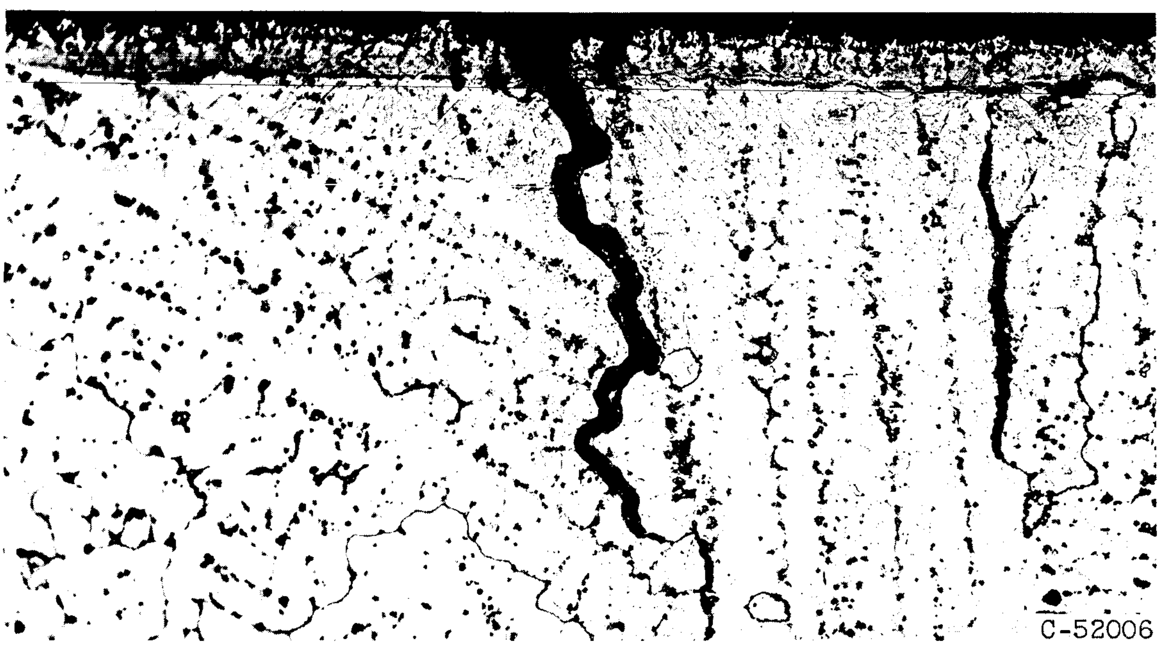


(d) Aluminized air-melted group-8 bucket operated 167.2 hours.

Figure 17. - Concluded. Typical microstructures of operated GMR 235 buckets. Electrolytically etched in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X750.

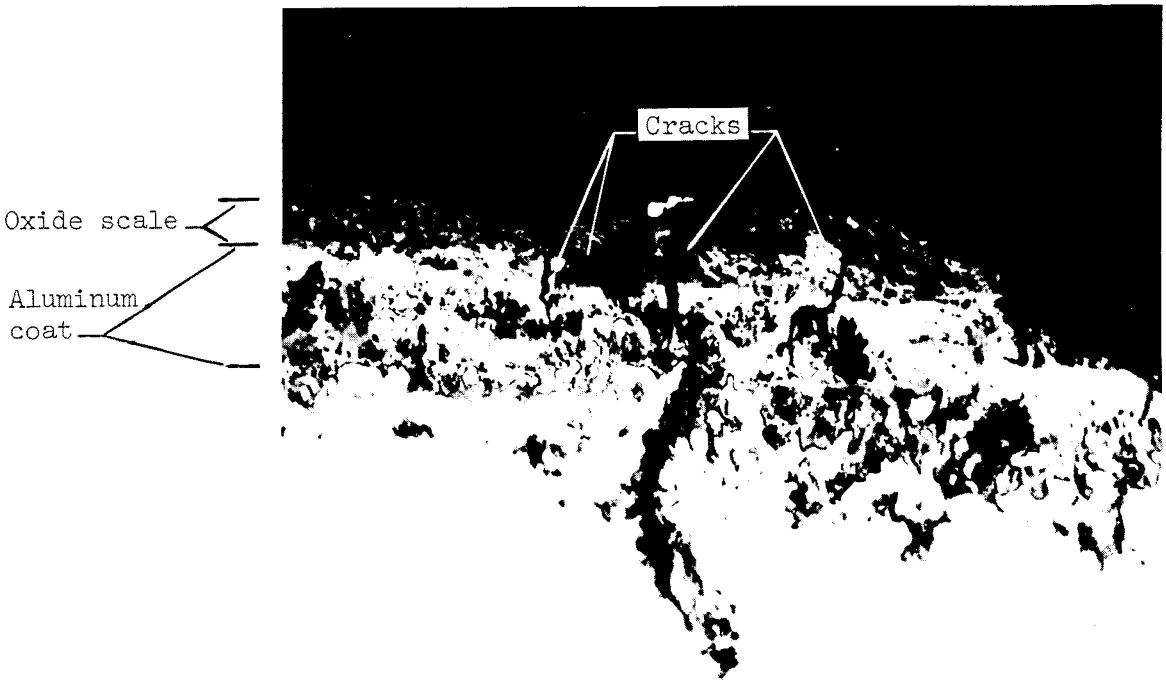


(a) Typical transgranular thermal-fatigue cracks. Etched electrolytically in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X100.



(b) Typical intergranular thermal-fatigue cracks. Etched electrolytically in a 40 percent hydrochloric acid, 10 percent nitric acid, 50 percent distilled water solution; X100.

Figure 18. - Types of thermal-fatigue cracks observed on leading edges of operated GMR 235 buckets.



C-52007

(c) Typical thermal-fatigue crack initiated in oxide scale of operated bucket. Unetched; X750.

Figure 18. - Concluded. Types of thermal-fatigue cracks observed on leading edges of operated GMR 235 buckets.